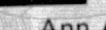


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25 - 29 April, 1977



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OF MICHIGAN**
Ann Arbor, Michigan



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Volume I

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Environmental Research Institute of Michigan

in cooperation with

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Extension Service

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Environmental Research Institute
of Michigan
Ann Arbor, Michigan

PROGRAM

MONDAY

APRIL 25 1530 [7]

0800 REGISTRATION, RACKHAM LOBBY

SESSION 1 (Rackham Lecture Hall)

OPENING REMARKS; KEYNOTE ADDRESS:
OVERVIEW

Presiding: G. J. ZISSIS, Environmental
Research Institute of
Michigan, Ann Arbor, MI

1020 [1] WELCOME AND INTRODUCTION
W. M. BROWN, President
ERIM, Ann Arbor, MI

1030 [2] KEYNOTE ADDRESS: THE
PROBLEMS AND OPPORTUNITIES
W. E. NIERENBERG, Director
Scripps Institution of
Oceanography, La Jolla, CA

1130 [3] THE TECHNOLOGICAL RESPONSE
D. J. FINK, Vice President
Space Division, General
Electric Co., Philadelphia,
PA

SESSION 2 (Rackham Lecture Hall)

SENSORS AND SENSOR DEVELOPMENT

Presiding: V. T. NORWOOD, Hughes Air-
craft Co., El Segundo, CA

1330 [4] EARTH REMOTE SENSING: USER
NEEDS AND TECHNOLOGY
OPPORTUNITIES
R. G. NAGLER, Jet Propulsion
Laboratory, Pasadena, CA

1400 [5] PROJECTIONS IN INFRARED AND
VISIBLE SENSORS
JOHN CARSON, Carson Alexiou
Corp., Newport Beach, CA

1430 [6] TECHNOLOGY ADVANCES IN
ACTIVE AND PASSIVE MICROWAVE
SENSING THROUGH 1985
F. T. BARATH, Jet Propulsion
Laboratory, Pasadena, CA

SESSION 3 (Rackham Lecture Hall)

HYDROLOGIC APPLICATIONS

Presiding: V. V. SALOMONSON, NASA,
Goddard Space Flight
Center, Greenbelt, MD

THE UTILITY OF SHORT WAVE-
LENGTH (<1mm) REMOTE
SENSING TECHNIQUES FOR THE
MONITORING AND ASSESSMENT
OF HYDROLOGIC PATTERNS
A. RANGO, NASA, Goddard
Space Flight Center,
Greenbelt, MD

1600 [8] MICROWAVE REMOTE SENSING OF
HYDROLOGIC PARAMETERS
F. T. ULABY, University of
Kansas, Lawrence, KS

1630 [9] UTILIZATION OF REMOTE
SENSING OBSERVATIONS IN
HYDROLOGIC MODELS
R. M. RAGAN, University of
Maryland, College Park, MD

SESSION 4 (Rackham Amphitheater)

GEOGRAPHIC APPLICATIONS

Presiding: R. L. SHELTON, Michigan
State University, East
Lansing, MI

1530 [10] THE IMPACT OF REMOTE SENSING
ON THE DISCIPLINE OF GEO-
GRAPHY: THE PAST IN PER-
SPECTIVE, PRESENT REALITIES,
FUTURE POTENTIALS
J. E. ESTES and D. SIMONETT,
University of California,
Santa Barbara, CA

1610 [11] REMOTE SENSING IN GEO-
GRAPHIC APPLICATIONS
J. R. ANDERSON, R. E.
WITMER and J. R. WRAY,
U.S. Geological Survey,
Reston, VA; and R. L.
SHELTON, Michigan State
University, East Lansing, MI

1650 DISCUSSION

TUESDAY

APRIL 26

SESSION 5 (Rackham Lecture Hall)

SENSOR DATA ANALYSIS AND INTERPRETATION

Presiding: J. D. ERICKSON, NASA,
Johnson Space Center,
Houston, TX

- 0830 [12] MULTISPECTRAL REMOTE SENSING DATA PROCESSING: TWO YEARS AGO, TODAY, AND TWO YEARS FROM NOW
Q. A. HOLMES, Environmental Research Institute of Michigan, Ann Arbor, MI; D. G. GOODENOUGH, Canada Centre for Remote Sensing, Ottawa, Ontario, Canada; and J. D. ERICKSON, NASA, Johnson Space Center, Houston, TX [P6]
- 0900 [13] A SURVEY OF SAR IMAGE-FORMATION PROCESSING FOR EARTH RESOURCE APPLICATIONS
R. W. BAYMA, Environmental Research Institute of Michigan, Ann Arbor, MI; R. L. JORDAN, Jet Propulsion Laboratory, Pasadena, CA; and B. N. MANNING, Goodyear Aerospace Corp., Litchfield Park, AZ [P8]
- 0930 [14] A PERSPECTIVE ON THE STATE OF THE ART OF AERIAL PHOTOGRAPHIC INTERPRETATION
J. E. ESTES, University of California, Santa Barbara, CA [P10]
- 1030 POSTER SESSION A
(Michigan League Ballroom)
- [P1] LANDSAT-D THEMATIC MAPPER SIMULATION USING AIRCRAFT MULTISPECTRAL SCANNER DATA
JERRY CLARK and NEVIN A. BRYANT, Jet Propulsion Laboratory, Pasadena, CA [P11]
- [P2] USE OF NEAR INFRARED/RED RADIANCE RATIOS FOR ESTIMATING VEGETATION BIOMASS AND PHYSIOLOGICAL STATUS
COMPTON J. TUCKER, NASA, Goddard Space Flight Center, Greenbelt, MD [P12]
- [P3] APPLICATION OF THE SUITS REFLECTANCE MODEL TO DISEASED RICE CANOPIES
G. KNOLL, Institut fur Physikalische Weltraumforschung, Freiberg, West Germany [P13]
- [P4] USE OF MULTISPECTRAL DATA IN DESIGN OF FOREST SAMPLE SURVEYS
S. J. TITUS and L. C. WENSEL, University of California, Berkeley, CA [P14]
- [P5] MONITORING IRRIGATED LAND ACREAGE USING LANDSAT IMAGERY: AN APPLICATION EXAMPLE
WILLIAM C. DRAEGER, Technicolor Graphic Services, Inc., Sioux Falls, SD
- INFLUENCE OF GROUND LEVEL SO_2 ON THE DIFFUSE TO DIRECT IRRADIANCE RATIO IN THE MIDDLE ULTRAVIOLET
K. F. KLENK and A.E.S. GREEN, University of Florida, Gainesville, FL
- THE VECTOR CLASSIFIER
K. R. McCLOY, South Australian Institute of Technology, Ingle Farm, South Australia
- MULTI-SEASONAL DATA ANALYSIS AND SOME EXTENSIONS FOR ENVIRONMENTAL MONITORING
SOTARO TANAKA and TADASHI MURANAKA, Remote Sensing Center of Japan; HIROSHI MIYAZAWA, Toyo Aero Survey Co., Ltd.; YUZO SUGA, Hosei University, Tokyo, Japan
- DIGITAL EXPLOITATION OF SYNTHETIC APERTURE RADAR
H. WAGNER and R. A. SHUCHMAN, Environmental Research Institute of Michigan, Ann Arbor, MI
- ENVIRONMENTAL STUDIES OF THE NEW BULLET TRAIN OF THE JOETSU LINE BY REMOTE SENSING TECHNIQUES
TAICHI OSHIMA, Hosei University, Tokyo, Japan
- ON THE PHOTOGRAPHIC PROCESSING AND DIGITAL TEXTURE FOR REMOTE SENSING OF KUJUKURI'S COAST OF CHIBA IN JAPAN
H. GENDA, Chiba University, K. TAKEDA, Science and Technology Agency and H. OKAYAMA, Chiba University, Chiba, Japan
- LANDSAT DETECTION OF HYDROTHERMAL ALTERATION IN THE NOGAL CANYON CALDRON, NEW MEXICO
ROBERT K. VINCENT, GeoSpectra Corp., Ann Arbor, MI; GEORGE ROUSE, Earth Sciences, Inc., Golden, CO
- AUTOMATED IMAGE PROCESSING OF LANDSAT 2 DIGITAL DATA, FOR WATERSHED RUNOFF PREDICTION
ROBERT R. SASSO, JOHN R. JENSEN, and JOHN E. ESTES, University of California, Santa Barbara, CA
- MICROWAVE MULTISPECTRAL INVESTIGATIONS OF SNOW
E. SCHANDA and R. HOFER, University of Berne, Berne, Switzerland

[P15] APPLICATION OF LANDSAT DATA TO WETLAND STUDY AND LAND USE CLASSIFICATION IN WEST TENNESSEE
N. L. JONES and F. SHAHROKHI
The University of Tennessee Space Institute, Tullahoma, TN

[P16] TESTING THE ACCURACY OF REMOTE SENSING LAND USE MAPS
J. L. VAN GENDEREN and P. A. VASS,
Fairey Surveys, Ltd., Berkshire,
England; B. F. LOCK, Salisbury
College of Advanced Education,
Adelaide, Australia

[P17] PRESENT AND FUTURE OPERATIONAL NOAA SATELLITE OCEANOGRAPHIC PRODUCTS: AN INTRODUCTION
J. K. KALINOWSKI, T. L. SIGNORE,
W. G. PICHEL, C. C. WALTON, R. L. BROWER, S. R. BROWN and K. G. BENNEKAMPER, National Environmental Satellite Service, Dept. of Commerce-NOAA, Suitland, MD

[P18] POLARIMETER MEASURES OF SEA STATE USING EMITTED INFRARED RADIATION
W. G. EGAN and T. HILGEMAN,
Grumman Aerospace Corp.,
Bethpage, NY

[P19] SCATTEROMETER RESULTS FROM SHORE-FAST AND FLOATING SEA ICE OBSERVED OFF THE CANADIAN EAST COAST
L. GRAY, J. CIHLAR, S. PARASHAR and R. WORSFOLD, Canada Centre for Remote Sensing, Ottawa, Ontario, Canada

[P20] REMOTE SENSING OF LAKE EUTROPHICATION
B. MØLLER SØRENSEN, B. STRUM and G. MARACCI, Joint Research Center, Ispra, Italy

[P21] AN OPERATIONAL, MULTISTATE, EARTH OBSERVATION DATA MANAGEMENT SYSTEM
L. F. EASTWOOD, JR., C. T. HILL, R. P. MORGAN and J. K. GOHAGEN,
Center for Development Technology, Washington University, St. Louis, MO

[P130] REINDEER RANGE INVENTORY IN WESTERN ALASKA FROM COMPUTER-AIDED DIGITAL CLASSIFICATION OF LANDSAT DATA
T. H. GEORGE, W. J. STRINGER and J. N. BALDRIDGE, Geophysical Institute, University of Alaska, Fairbanks, AK

[P133] REMOTE SENSING EXPLORATION FOR METALLIC MINERAL RESOURCES IN BAJA CALIFORNIA
RALPH N. BAKER, Space Division, General Electric Co., Beltsville, MD

SESSION 6 (Rackham Lecture Hall)

GEOLOGY AND MINERAL RESOURCES

Presiding: W. R. HEMPHILL, EROS Program, USGS, Reston, VA

1330 [15] GEOLOGIC LINEARS: REMOTELY SENSED BONANZAS AND EXTRA-VAGANZAS
D. U. WISE, University of Massachusetts, Amherst, MA

1400 [16] COMPARATIVE PLANETOLOGY - IDEAS AND METHODOLOGY: THEIR APPLICATION TO TERRESTRIAL GEOLOGIC PROCESSES
H. MASURSKY, USGS, Flagstaff, AZ

1430 [17] INDUSTRIAL USE OF GEOLOGICAL REMOTE SENSING FROM SPACE
F. B. HENDERSON, Geosat Committee, San Francisco, CA

SESSION 7 (Rackham Amphitheater)

METEOROLOGICAL APPLICATIONS

Presiding: H. S. MOORE, National Oceanic and Atmospheric Administration, Rockville, MD

1330 [18] METEOROLOGICAL SENSORS & RELATED TECHNOLOGY FOR THE EIGHTIES
L. HEACOCK, National Environmental Satellite Service, NOAA, Suitland, MD

1400 [19] OPERATIONAL DATA PROCESSING-THE FIRST TEN YEARS ARE THE HARDEST
J. A. LEESE and C. L. BRISTOR, National Environmental Satellite Service, NOAA, Suitland, MD

1430 [20] OPERATIONAL UTILIZATION OF REMOTELY SENSED DATA
J. B. JONES, National Weather Service, NOAA, Silver Spring, MD

- 1530 POSTER SESSION B
(Michigan League Ballroom)
- [P22] INVESTIGATION OF THEMATIC MAPPER SPATIAL, RADIOMETRIC, AND SPECTRAL RESOLUTION
J. P. MORGENSTERN and R. F. NALEPKA, Environmental Research Institute of Michigan, Ann Arbor, MI; J. D. ERICKSON, NASA, Johnson Space Center, Houston, TX
- [P23] THEORETICAL AND EXPERIMENTAL TESTS OF THE SUITS REFLECTANCE MODELS FOR WHEAT AND COTTON
J. E. CHANGE and E. W. LeMASTER, Pan American University, Edinburg, TX
- [P24] ESTIMATION OF OLD FIELD ECOSYSTEM BIOMASS USING LOW ALTITUDE IMAGERY
S. M. NOR, G. SAFIR, T. M. BURTON, J. E. HOOK and G. SCHULTINK, Michigan State University, East Lansing, MI
- [P25] THE EFFECT OF SOIL WATER DEFICIT ON THE MEASURED REFLECTANCE OF CONIFER SEEDLINGS IN MICHIGAN
LAWRENCE FOX III, Humboldt State University, Arcata, CA
- [P26] DIGITAL ANALYSIS OF LANDSAT DATA FOR SURVEYING NATURAL RESOURCES IN WESTERN SUDAN
M. BAUMGARDNER and S. KRISTOF, LARS, Purdue University, West Lafayette, IN; Y. YAGOUR, Ministry of Agriculture, Food and Natural Resources, Khartoun, Sudan
- [P27] EMPIRICAL CORRECTION FOR ATMOSPHERIC AEROSOLS IN LANDSAT IMAGES
M. M. TAYLOR, Defense & Civil Institute of Environmental Medicine, Downsview, Ontario, Canada; E. J. LANGHAM, Department of Fisheries & Environment, Ottawa, Ontario, Canada
- [P28] USE OF CLEAR LAKES AS STANDARD REFLECTORS FOR ATMOSPHERIC MEASUREMENTS
F. J. AHERN, D. G. GOODENOUGH, S. C. JAIN and V. R. RAO, Canada Centre for Remote Sensing, Ottawa Ontario, Canada; G. ROCHON, Laval University, Quebec City, Quebec, Canada
- [P29] A LOW-COST SYSTEM FOR RECEPTION AND HANDLING OF LINE-SCAN DATA FROM LANDSAT AND OTHER SOURCES
D. S. SLOAN, B. C. ISHERWOOD and J. S. MacDONALD, MacDonald Dettwiler & Associates, Ltd., Vancouver, British Columbia, Canada
- [P30] THE USE OF LANDSAT IMAGERY TO LOCATE UNCHARTED COASTAL FEATURES ON THE LABRADOR COAST
E. A. FLEMING, Surveys and Mapping Branch, EMR; D. D. LeLIEVRE, Canadian Hydrographic Service, Ottawa, Ontario, Canada
- [P31] ALTERATION MAPPING AT GOLDFIELD, NEVADA, BY CLUSTER AND DISCRIMINANT ANALYSIS OF LANDSAT DIGITAL DATA
GARY BALLEW, Stanford University, Stanford, CA
- P32 QUATERNARY GEOLOGIC MAP OF MINNESOTA
JOSEPH E. GOEBEL, University of Minnesota, St. Paul, MN
- [P33] REMOTE SENSING-AIDED SYSTEMS FOR SNOW QUANTIFICATION, EVAPOTRANSPIRATION ESTIMATION, AND THEIR APPLICATION IN HYDROLOGIC MODELS
SIAMAK KHORRAM, University of California, Berkeley, CA
- [P34] APPLICATION OF AERIAL PHOTOGRAPHY TO WATER-RELATED PROGRAMS IN MICHIGAN
W. R. ENSLIN, K. HILL-ROWLEY and S. E. TILMANN, Michigan State University, East Lansing, MI
- [P35] AQUATIC PLANT REMOTE SENSING
K. S. LONG and L. E. LINK, JR., U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS
- [P36] PRODUCTION OF A MAP OF LAND-USE IN IOWA THROUGH MANUAL INTERPRETATION OF LANDSAT IMAGERY
RAYMOND R. ANDERSON, Iowa Geological Survey, Iowa City, IA
- [P37] THE APPLICATION OF IR- AND MSS-DATA IN THE RUHR DISTRICT, GERMANY
P. STOCK, Siedlungsverband Ruhrkohlenbezirk, Essen, West Germany
- [P38] POTENTIAL APPLICATIONS OF DIGITAL, VISIBLE AND INFRA-RED DATA FROM GEOSTATIONARY ENVIRONMENTAL SATELLITES
D. B. MILLER, J. D. TARPLEY, M. P. WATERS, III, and R. N. GREEN, National Environmental Satellite Service, Dept. of Commerce, NOAA, Suitland, MD
- [P39] STUDY OF THE BRAZIL AND FALKLAND CURRENTS USING THEIR IMAGES OF NIMBUS V AND OCEANOGRAPHIC DATA IN 1972 TO 1973
Y. C. TSENG, H. M. INOSTROZA V. and R. KUMAR, Instituto de Pesquisas Espaciais, S.Paulo, Brazil

- [P40] NASA/COUSTEAU OCEAN BATHYMETRY EXPERIMENT
FABIAN C. POLCYN, Environmental Research Institute of Michigan, Ann Arbor, MI 0900
- [P41] LANDSAT DIGITAL DATA FOR WATER POLLUTION AND WATER QUALITY STUDIES IN SOUTHERN SCANDINAVIA
ULF HELLDEN, University of Lund, Lund, Sweden; INGVAR AKERSTEN, National Defence Research Institute, Stockholm, Sweden 0930
- [P42] INDICATORS OF INTERNATIONAL REMOTE SENSING ACTIVITIES
G. WILLIAM SPANN, METRICS, Inc., Atlanta, GA 1030
- [P129] QUANTITATIVE EVALUATION OF DYNAMIC WATER BODIES BY MEANS OF THERMAL INFRARED AND MULTI-SPECTRAL SURVEYS ON THE VENETIAN LAGOON
L. ALBEROTANZA and G. M. LECHI, Istituto Per La Geofisica Della Litosfera, Milano, Italy
- [P134] A RECTANGULAR COORDINATE SYSTEM FOR GEOMETRICALLY CORRECTED LANDSAT MSS IMAGES
F. TRAGNI, Lockheed Electronics Co., Inc., Houston, TX
- 1830 SOCIAL HOUR AND BANQUET
- BANQUET ADDRESS "REBIRTH OF REMOTE SENSING - DO WE KNOW ENOUGH FOR OUR OWN GOOD?"
THE HONORABLE ROBERT L. HERBST, Assistant Secretary of the Interior for Fish and Wildlife and Parks, Washington, D.C.
- WEDNESDAY APRIL 27
- SESSION 8
(Rackham Lecture Hall)
- ECONOMIC AND INSTITUTIONAL ISSUES
- Presiding: K. P. HEISS, ECON, Inc., Princeton, NJ
- 0830 [21] GATHERING AND USING INFORMATION ON A GLOBAL SCALE
C. W. MATHEWS, Consultant, Senate Aeronautical and Space Sciences Committee, Washington, D.C.
- [22] U.S. INITIATIVES FOR REMOTE SENSING APPLICATIONS IN THE DEVELOPING WORLD
J. K. WILHELM, U.S. Agency for International Development, Department of State, Washington, D.C.
- [23] THE PRESENT STATUS OF REMOTE SENSING IN THE UNITED NATIONS
E. GALLOWAY, International Institute of Space Law of the International Astronautical Federation, Washington, D.C.
- PANEL DISCUSSION
- POSTER SESSION C
(Michigan League Ballroom)
- [P43] VIZIR - THE SEP HIGH RESOLUTION IMAGERY DISPLAY UNIT - PRINCIPLE PERFORMANCES - FIELDS OF APPLICATION
M. L. SALTER and M. G. MAINCENT, Societe Europeene de Propulsion, Vernon, France
- [P44] TWO PHASE SAMPLING FOR WHEAT ACREAGE ESTIMATION
R. W. THOMAS and C. M. HAY, University of California, Berkeley, CA
- [P45] CLASSIFICATION OF LANDSAT AGRICULTURAL DATA BASED UPON COLOR TRENDS
J. D. TUBBS, University of Arkansas, Fayetteville, AR
- [P46] THE USE OF LANDSAT DIGITAL DATA TO DETECT AND MONITOR VEGETATION WATER DEFICIENCIES
DAVID R. THOMPSON and OSCAR A. WEHMANEN, NASA, Johnson Space Center, Houston, TX
- [P47] PRE-VISUAL DETECTION OF FOREST STRESS
CHARLES E. OLSON, JR., The University of Michigan, Ann Arbor, MI
- [P48] VIEW ANGLE EFFECT IN LANDSAT IMAGERY
TOYOHISA KANEKO, IBM Corp.; JOHN L. ENGVALL, NASA, Johnson Space Center, Houston, TX
- [P49] LAND USE CLASSIFICATION USING OPTICAL POWER SPECTRUM ANALYSIS: A FURTHER STUDY OF PARAMETER DEPENDENCIES
D. L. TINGEY, Boeing Aerospace Corp., Seattle, WA

- [P50] INTERACTIVE IMAGE PROCESSING TECHNIQUES USING THE PLESSEY IDP 3000
O. E. MORGAN, D. M. BALSTON and N.D.E. CUSTANCE, Plessey Radar Research Centre, Hampshire Havant, England
- [P51] APPLICATION OF REMOTE SENSING TO THE SITING OF THE WARM SPRINGS DAM, SOMONA COUNTY, CALIFORNIA
ROBERT REED, Dames & Moore, Cranford, NJ
- [P52] CARTOGRAPHIC SUITABILITY OF LANDSAT IMAGERY
A. K. BAGCHI, University of Roorkee, Roorkee, India
- [P53] REMOTE INFRARED SPECTROSCOPY OF THE EARTH
R. STEINMANN, Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt, Köln, West Germany
- [P54] IMAGE ANALYSIS TECHNIQUES WITH SPECTRAL REFERENCE TO ANALYSIS AND INTERPRETATION OF GEOLOGICAL FEATURES FROM LANDSAT IMAGERY
D. S. KAMAT, L. K. MAJUMDER and V. L. SWAMINATHAN, Space Applications Centre, Ahmedabad, India
- [P55] MULTIDATE MAPPING OF MOSQUITO HABITAT
THOMAS WOODZICK and EUGENE L. MAXWELL, Colorado State University, Fort Collins, CO
- [P56] LATE WISCONSINAN DEGLACIATION OF THE NORTHERN MIDWEST INTERPRETED FROM A SPRINGTIME LANDSAT COLOR MOSAIC
JAMES R. LUCAS, Technicolor Graphic Services, Inc.; JAMES V. TARANIK, U.S. Geological Survey, Sioux Falls, SD
- [P57] NECESSITY TO ADAPT LAND USE AND LAND COVER CLASSIFICATION SYSTEMS TO READILY ACCEPT RADAR DATA
BEN DRAKE, Old Dominion University, Norfolk, VA
- [P58] APPLICATION OF AIRBORNE INFRARED TECHNOLOGY TO MONITOR BUILDING HEAT LOSS
ROBERT E. SAMPSON and FRED J. TANIS, Environmental Research Institute of Michigan, Ann Arbor, MI
- [P59] PROCESSING OF SATELLITE IMAGERY AT THE NATIONAL ENVIRONMENTAL SATELLITE SERVICE
M. CROWE, National Environmental Satellite Service, U.S. Dept. of Commerce-NOAA, Suitland, MD
- [P60] REMOTE SENSING OF OCEAN COLOR AND DETECTION OF CHLOROPHYLL CONTENT
P. Y. DESCHAMPS, P. LECOMTE and M. VIOLLIER, Université de Lille, Villeneuve D'Ascq., France
- [P61] TEXTURAL ANALYSIS BY STATISTICAL PARAMETERS AND ITS APPLICATION TO THE MAPPING OF FLOW-STRUCTURES IN WETLANDS BY AERIAL PHOTOGRAPHS
ULRICH WIECZOREK, Universität München, München, West Germany
- [P62] PRODUCTION OF A WATER QUALITY MAP OF SAGINAW BAY BY COMPUTER PROCESSING OF LANDSAT-2 DATA
JOHN B. McKEON and ROBERT H. ROGERS, Bendix Aerospace Systems Division, Ann Arbor, MI; V. ELLIOTT SMITH, Cranbrook Institute of Science, Bloomfield Hills, MI
- [P63] REMOTE SENSING UTILIZATION BY DEVELOPING COUNTRIES: AN APPROPRIATE TECHNOLOGY
M. W. CONITZ, U.S. Agency for International Development, Washington, D.C. and D. S. LOWE, Environmental Research Institute of Michigan, Ann Arbor, MI
- [P131] IMPACT OF ENVIRONMENTAL INFORMATION FROM LANDSAT TO PETROLEUM EXPLORATION IN THE GULF OF ALASKA
J. M. MILLER, University of Alaska, Fairbanks, AK
- [P135] SURVEY OF USERS OF EARTH RESOURCES REMOTE SENSING DATA
G. E. WUKELIC, J. G. STEPHAN, H. E. SMAIL and T. F. EBBERT, Battelle, Columbus Laboratories, Columbus, OH

SESSION 9
(Rackham Lecture Hall)

AGRICULTURE, FORESTRY,
RANGELAND RESOURCES

Presiding: A. B. PARK, Space Division,
General Electric Company,
Beltsville, MD

ORIGINAL PAGE IS
OF POOR QUALITY

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- 1400 [25] REMOTE SENSING AND TODAY'S FORESTRY ISSUES
L. SAYN-WITTGENSTEIN, Forest Management Institute, Canadian Forestry Service, Ottawa, Ontario, Canada
- 1430 [26] REMOTE SENSING IN RANGELAND MANAGEMENT: AN OVERVIEW OF APPLICATIONS AND BENEFITS
D. M. CARNEGIE, EROS Data Center, USGS, Sioux Falls, SD
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(Rackham Amphitheater)
- OCEAN AND COASTAL APPLICATIONS
- Presiding: V. KLEMAS, University of Delaware, Newark, DE
- 1330 [27] CURRENT AND FUTURE SATELLITES FOR OCEAN MONITORING
J. W. SHERMAN, III, National Environmental Satellite Service, NOAA, Suitland, MD
- 1400 [28] OUTLOOK FOR REMOTE SENSING IN THE COASTAL ZONE
P. G. TELEKI and A. N. KOVER, U.S. Geological Survey, Reston, VA
- 1430 [29] COASTAL WETLANDS IN RELATION TO THE PRESENT AND FUTURE ROLE OF REMOTE SENSING
V. CARTER, U.S. Geological Survey, Reston, VA
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S. WALTER McCANDLESS, JR., NASA, Washington, D.C.
- [P65] EVALUATION OF SPECTRAL CHANNELS AND WAVELENGTH REGIONS FOR SEPARABILITY OF AGRICULTURAL COVER TYPES
R. KUMAR, Instituto de Pesquisas Espaciais (INPE), S. Paulo, Brazil
- [P66] THERMAL IMAGERY FOR CENSUS OF UNGULATES
MARC C. WRIDE, INTERA Environmental Consultants, Ltd.; KEITH BAKER, Parks Canada, Calgary, Alberta, Canada
- [P67] REMOTE SENSING IN OPERATIONAL RANGE MANAGEMENT PROGRAMS IN WESTERN CANADA
M. DIANE THOMPSON, INTERA Environmental Consultants, Ltd., Calgary, Alberta, Canada
- [P68] AN APPLICATION OF LANDSAT DIGITAL TECHNOLOGY TO FOREST FIRE FUEL TYPE MAPPING
P. KOURTZ, Forest Fire Research Institute, Ottawa, Ontario, Canada
- [P69] LANDSAT IMAGE INTERPRETATION AIDS
R. A. ABOTTEEN and H. MALEK, Lockheed Electronics Co., Houston, TX
- [P70] DIGITAL PROCESSING SYSTEM FOR DEVELOPING COUNTRIES
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- [P72] INTEGRATION OF REMOTE SENSING AND SURFACE GEOPHYSICS IN THE DETECTION OF FAULTS
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- [P73] EVALUATION OF ALGORITHMS FOR GEOLOGICAL THERMAL INERTIA MAPPING
S. H. MILLER and KEN WATSON, U.S. Geological Survey, Denver, CO
- [P74] USE OF THERMAL-INFRARED IMAGERY IN GROUND-WATER INVESTIGATIONS, MONTANA
A. J. BOETTCHER and R. M. HARALICK, U.S. Geological Survey, Helena, MT

- [P75] SATELLITE LAND USE ACQUISITION AND APPLICATION TO HYDROLOGIC PLANNING MODELS
R. ALGAZI and M. SUK, University of California, Davis, CA
- [P76] LAND UTILIZATION AND ECOLOGICAL ASPECTS IN THE SYLHET-MYMENSINGH HAOR REGION OF BANGLADESH: AN ANALYSIS OF LANDSAT DATA
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- [P83] APPLICATION OF LANDSAT TO MAPPING INLAND LAKE WATER QUALITY AND WATERSHED LAND USE
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R. O. CHIPMAN, formerly Outer Space Affairs Division, United Nations, New York, NY
- 0920 [32] TRANSFER OF REMOTE SENSING TECHNOLOGY FROM THE UN AND INDUSTRIALIZED NATIONS TO OTHER NATIONS-NEED FOR A GUIDED APPROACH
A. A. ABIODUN, Department of Agricultural Engineering, University of Ife, Ile-Ife, Nigeria

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- [P86] COMPUTER AIDED CLASSIFICATION FOR REMOTE SENSING IN AGRICULTURE AND FORESTRY IN NORTHERN ITALY
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- [P87] THE INFLUENCE OF MULTISPECTRAL SCANNER SPATIAL RESOLUTION ON FOREST FEATURE CLASSIFICATION
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- [P88] REDUCING LANDSAT DATA TO PARAMETERS WITH PHYSICAL SIGNIFICANCE AND SIGNATURE EXTENSION-REALISTIC, ALTHOUGH CYNICAL, VIEW OF LANDSAT CAPABILITIES
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- [P89] AERIAL ALBEDOS OF NATURAL VEGETATION IN SOUTH-EASTERN AUSTRALIA
J. A. HOWARD, Food and Agriculture Organization, Rome, Italy
- [P90] BLOB, AN UNSUPERVISED CLUSTERING APPROACH TO SPATIAL PREPROCESSING OF MSS IMAGERY
R. KAUTH, A. PENTLAND and G. THOMAS, Environmental Research Institute of Michigan, Ann Arbor, MI
- [P91] MULTISPECTRAL SYSTEM ANALYSIS THROUGH MODELING AND SIMULATION
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- [P92] A 'DIGITAL' TECHNIQUE FOR MANUAL EXTRACTION OF DATA FROM AERIAL PHOTOGRAPHY
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- [P94] APPLICATION OF LANDSAT SATELLITE IMAGERY FOR IRON ORE PROSPECTING IN THE WESTERN DESERT OF EGYPT
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- [P95] GROUND WATER STUDIES IN ARID AREAS IN EGYPT USING LANDSAT SATELLITE IMAGES
E. M. EL SHAZLY, M. A. ABDEL HADY and M. M. EL SHAZLY, Remote Sensing Center, Cairo, Egypt
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- [P99] METEOROLOGICAL SUPPORT FOR REMOTE SENSING PROGRAMS
JAMES L. COX, Spaceflight Meteorological Group, National Weather Service, NOAA, Camp Springs, MD
- [P100] SATELLITE-TO-GROUND TRANSMISSIONS FOR AMATEURS AND PROFESSIONALS
ROBERT W. POPHAM, National Environmental Satellite Service, U.S. Department of Commerce, NOAA, Suitland, MD

[P101] USE OF AN INERTIAL NAVIGATION SYSTEM FOR ACCURATE TRACK RECOVERY AND COASTAL OCEANOGRAPHIC MEASUREMENTS
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W. E. SIVERTSON, JR., NASA, Langley Research Center, Hampton, VA; R. W. LARSON, Environmental Research Institute of Michigan, Ann Arbor, MI
J. S. ZELENKA, Science Applications, Inc., Tucson, AZ

[P106] PROTOTYPE ACTIVE SCANNER FOR NIGHTTIME OIL SPILL MAPPING AND CLASSIFICATION
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J. P. MILLARD, NASA, Ames Research Center, Moffett Field, CA; R. D. JACKSON, R. J. REGINATO, S. B. IDSO, USDA, Agricultural Research Service, Phoenix, AZ; R. C. GOETTELMAN, LFE Corp., Richmond, CA; and R. L. LAPADO, ESL Corp., Sunnyvale, CA

SESSION 12 (Rackham Lecture Hall)

ENVIRONMENTAL QUALITY

Presiding: S. H. MELFI, Environmental Monitoring and Support Laboratory, U.S. Environmental Protection Agency, Las Vegas, NV

1330 [33] REMOTE SENSING OF AIR POLLUTION
J. A. ECKERT, Environmental Monitoring and Support Laboratory, U.S. Environmental Protection Agency, Las Vegas, NV

[34] REMOTE SENSING OF WATER POLLUTION
W. A. HOVIS, Environmental Satellite Service, NOAA, Suitland, MD

[35] REMOTE SENSING OF ENVIRONMENTAL IMPACT OF LAND USE ACTIVITIES
C. K. PAUL, National Aeronautics and Space Administration, Washington, D.C.

SESSION 13 (Rackham Amphitheater)

ENGINEERING APPLICATIONS

Presiding: T. C. VOGEL, U.S. Army Engineering Topographic Laboratory, Ft. Belvoir, VA

1330 [36] THE ROLE OF REMOTE SENSING IN THE BUILDING OF THE INTERSTATE HIGHWAY SYSTEM
H. T. RIB, Federal Highways Administration, Washington, D.C.

1400 [37] REMOTE MONITORING AND TENNESSEE VALLEY AUTHORITY PROGRAMS
A. R. STEVENS, Tennessee Valley Authority, Chattanooga, TN

1430 [38] CORPS OF ENGINEERS APPLICATIONS FOR REMOTE SENSING OF THE ENVIRONMENT
COL. M. K. KURTZ, JR., Engineer Topographic Laboratories, Ft. Belvoir, VA; and J. W. JARMAN, Office of the Chief of Engineers, Corps of Engineers, Washington, D.C.

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Survey, Denver, CO
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space Systems Division, Ann
Arbor, MI
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Nevada, Reno, NV
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Lockheed Electronics Company,
Houston, TX
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NASA, Goddard Space Flight
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EDGERTON and D. C. MEEKS, Aero-
jet ElectroSystems Company,
Azusa, CA
- SESSION 14
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- MICROWAVE REMOTE SENSING
- Presiding: E. SCHANDA, Institute of
Applied Physics, University
of Berne, Berne,
Switzerland
- 1930 [39] ATMOSPHERIC SOUNDING WITH
PASSIVE MICROWAVES: REVIEW
AND PROGNOSIS
DAVID H. STAEELIN,
Massachusetts Institute of
Technology, Cambridge, MA
- 2000 [40] SPACE RADAR SYSTEM SPECIFI-
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F. T. ULABY, T. F. BUSH and
W. H. STILES, University of
Kansas, Lawrence, KS
- 2030 [41] APPLICATION OF SYNTHETIC
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ADAM KOZMA and RICHARD W.
LARSON, Environmental
Research Institute of
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- 2100 PANEL DISCUSSION
- FRIDAY APRIL 29
- SESSION 15
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- Presiding: G. J. ZISSIS, Environmental
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Johnson Space Center,
J. MURPHY, U.S. Department
of Agriculture; and J. D.
HILL, NOAA, Houston, TX
- 0900 [43] FUTURE EARTH RESOURCES
SATELLITE PROGRAMS
LEONARD JAFFE, NASA
Headquarters, Washington,
D.C.
- 0930 [44] ENERGY AND REMOTE SENSING
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Research and Development
Administration, Washington,
D.C.
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- 1030 PANEL DISCUSSION-OPERATIONAL
REMOTE SENSING
L. JAFFE-NASA Headquarters
L. W. MORLEY, Canada Centre
for Remote Sensing
A. B. PARK, General Electric Co
R. A. SUMMERS, Energy Research
and Development Administration

ABSTRACT

These Proceedings contain papers presented at the Eleventh International Symposium on Remote Sensing of Environment, held April 25th through 29th, 1977, on the campus of The University of Michigan, Ann Arbor, Michigan. This symposium, conducted by the Environmental Research Institute of Michigan, is part of a continuing program investigating current activities in the field of remote sensing. The meeting is primarily intended to stimulate an exchange of information on numerous aspects of the field, through the presentation of reports on work planned, in progress, or completed.

Presentations contained herein include those concerned with the utilization of this technology in various national and international programs as well as in numerous applications for monitoring and managing the earth's resources and man's global environment. Ground-based, airborne and spaceborne sensor systems and both manual and machine-assisted data analysis and interpretation are included.

EDITORIAL NOTE

Papers contained in these Proceedings have been included in the order of presentation at the symposium, while manuscripts not received in time to meet publication deadlines are, wherever possible, represented by comprehensive summaries.

An author index and the revised program are included as supplements to the table of contents. All illustrative materials have been reproduced in black and white except where individual authors elected to provide their own color prints. Readers are requested to contact specific authors where color prints of black and white figures are desired.

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WELCOME AND INTRODUCTION

William M. Brown
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Ladies and Gentlemen:

On behalf of the Ann Arbor community, The University of Michigan, the many sponsoring and contributing organizations for the program, and of course on behalf of my organization, The Environmental Research Institute of Michigan, it is a great pleasure to welcome you to the Eleventh International Symposium on Remote Sensing of Environment. This series of symposia started in 1962 when a relatively small group of people from U.S. government agencies and universities met to discuss the possibilities of applying modern sensor technology and associated data processing capabilities to the assessment of earth resources and to the monitoring of the environment. During the fifteen years since our first symposium, great strides have been made in remote sensing technology and its applications. The progress is perhaps best exemplified by the Landsat series of satellite systems. The data provided by the Landsat systems are being utilized throughout the world in a wide range of important applications. The applications vary in scale from local land use analysis to the LACIE program, which is a large scale multi-agency program to monitor and project wheat production on a world wide basis.

The broadened interest and capabilities in remote sensing which have developed throughout the world are critically needed in connection with the management of the earth's natural resources. People everywhere have come to realize that nature is finite. We are all concerned with the interplay between the world's growing population, limited food supply, the depletion of our available fossil fuels, and the demands placed on our other renewable and non-renewable resources. Remote sensing is a major technology required to help us cope with these major problem areas. Thus, you attendees and others working in remote sensing can contribute greatly to society's ability to wisely manage our earth resources and monitor and improve our environment.

As a matter of basic policy this symposium has pursued a strong international character, and I am sure that I speak for all U.S. attendees when I extend a special welcome to the many non-U.S. speakers and attendees. We are very pleased that approximately one-third of the papers for this meeting are from other nations of the world. As a technology remote sensing has a very special role to play in the international arena in that remote sensing provides an exceptionally good vehicle for international cooperation. The point is that this technology serves as a basis for major multi-national programs, and I think we who work in remote sensing should do all we can to advance remote sensing programs which foster improved international relations.

To summarize my brief remarks we see that remote sensing is an extremely important technology which directly impacts two of the world's major problem areas: man's ability to live in harmony with his neighbors, especially neighbors in other countries, and his ability to live in harmony with the rest of nature. I hope and trust that you find this meeting informative and rewarding. All of us at ERIM are pleased to have a part in conducting the program, and if we can be of further service please let us know. Also, if you have suggestions for future meetings please feel sincerely invited to provide comments to Dr. Jerald Cook or other members of the Executive or Program Committees.

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THE PROBLEMS AND OPPORTUNITIES*

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The first point to make - and immediately - is that I will not define remote sensing. After all, it was even used by Noah when he sent out the dove and it returned with the flowering peach spring in its beak - indicating that the flood was over.

I do plan to talk about remote sensing application to study the world's oceans, but even this is too broad for my purposes today. After all, oceanographers have been using acoustics for profiling the ocean bottom for years - and then the marine geologists principal tool is seismic exploration of the layers beneath the ocean. More recently, the antisubmarine warfare role of sound has been reversed and it is now being employed as a remote sensing tool for exploring the inhomogeneities of the ocean waters. I want to take time from the main stream of my talk to talk about remote sensing of the oceans interior. As is well known, the ocean is not homogeneous either vertically or horizontally. The vertical variation of the speed of sound is what leads to the deep sound channel and the focussing so important in ASW using low frequency sound. This has been exploited to extreme limits of coherency in length and time. Ultimately, signal processing is limited by inhomogeneities in composition and currents. However, these oceanic variations are important in themselves for a whole variety of oceanic processes such as vertical diffusion. This means that this noise or "acoustic clutter" can be put to use by acoustic remote sensing to yield important information to physical and biological oceanographers in much the same way that acoustic interaction with the bottom is useful to the marine geologist. We will then be modern in this talk and talk about the current status, opportunities, and shortcomings of satellite oceanography.

The principal application at this time is to superficial physical oceanography. This is because the basic sensor - high frequency electromagnetic radiation does not penetrate the ocean to any appreciable depth. Therefore, unless an internal phenomenon has surface expression, it is unobserved. One positive example is internal waves. Even so, there are two broad classes of phenomena - those that are directly linked to the surface, such as the ocean waves and the ocean height - and those tied to the flow of the waters - the ocean currents.

We can get some appreciation of what can be done from satellites by comparison with what is being done in meteorology. The oceans and the atmosphere both are geophysical fluids obeying very similar laws and the comparison should be just a matter of scaling.

*Keynote address given at the Eleventh International Symposium on Remote Sensing of Environment, Ann Arbor, Michigan, April 25, 1977.

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First we examine the length scales by using the Rossby radius of deformation (Slide 1, Figure 1).

$$L = \frac{D\eta}{\omega}$$

$\omega = 2 \sin \phi$ the Coriolis parameter

Ω = angular velocity of rotation of the earth

ϕ = latitude

D = fluid depth

$\eta = -\frac{1}{\rho} \frac{d\phi}{dz}$ the Vaisala frequency

For the atmosphere we chose $D=10^4$ m, $\omega = 1/60 \text{ sec}^{-1}$

$\omega = 1.5 \times 10^{-4} \sin \phi$ yielding

$$L \approx 1200 \text{ km}$$

For the oceans we have $D=4 \times 10^3$ m, $\omega = 5 \times 10^{-3} \text{ sec}^{-1}$

yielding $L \approx 130 \text{ km}$

We now take up the time scale using the Rossby frequency

$$\sigma = \beta/\kappa \text{ or } T = \frac{2\pi\kappa}{\beta}$$

σ = wave frequency $= \frac{2\Omega \cos \phi}{R}$, the variation of with distance along the meridian (Slide 1a, Figure 1a).

If we take $\kappa = \frac{1}{L} = \frac{\omega}{D\eta}$,

$$\text{We get } T = \frac{2\pi R}{\eta D}$$

giving typical values $T \approx 100$ hours in the atmosphere

$T \approx 1000$ hours in the ocean.

The velocity scaling can, of course, be obtained from the ratio of length to time scales. We assume that the waves are near the limit where the particle velocities are $\approx$ wave phase velocities - the motion is not quite wave-like not quite turbulent.

What does this mean in terms of satellite coverage - oceans versus atmosphere?

Obviously, to get the same two dimensional sampling for typical wavelengths, the data rate for oceanic areal coverage is 100 times that for the atmosphere. On the other hand, the oceanic processes are 10 times slower so the net data rate for the oceans is 10 times that for the atmosphere. This ratio is further reduced by the physical limitations. In the atmosphere, the data is sampled at various depths while for the ocean, it can only be taken at the surface.

With this background we can examine more precisely the relationship of satellite oceanography to some modern oceanographic developments. There have been several different approaches to the common viewpoint but perhaps the Walter Munk statement covers it the most succinctly. He pointed out that for many years oceanographers worked with a DS. picture of the larger features of the world ocean. In recent years, the AC. picture is becoming more and more delineated. The familiar DC. maps of the world's currents do not prove very useful for the description of many important oceanic processes. It is particularly unsuitable for coupling to the atmosphere in terms of our weather and for dealing with climate changes of periods between several months and years for example.

A most recent global study by Wyrski from Hawaii of the relative energy in the fluctuating part of the current (the eddy) versus the DC. component shows that there is perhaps ten times the energy in the time variable component than in the DC. component. It is not simply that oceanographers were not aware of this possibility - there were indications enough but the measurements with the ships and equipment available were inadequate to the problem. Still NORPAX and its predecessors showed that the scale lengths of these variations seemed correct based on the anomalous surface sea temperatures of the northern Pacific and similarly with the scale periods (Slide 2, Figure 2).

The similarity to the atmospheric variation of related scale has caused oceanographers to speak of ocean "weather" and ocean "storms" in the same sense assuming that the fundamental length of this eddy energy is the meso-scale. However, efforts to demonstrate the existence of these mesoscale phenomena in the barest outlines, have been cumbersome and expensive. The Russian Polygon and the U.S. MODE experiments are for this purpose.

It is perhaps too ambitious and probably unnecessary to make regular synoptic observations of the oceans as we do the atmosphere. The character of atmospheric observations are as determined, at least as much by direct applications such as to agriculture, aviation, construction and so on as it is for theoretical work. The oceanic practical requirements are different from the atmospheric so the use of the word "weather" may carry more meaning than is desired. Nevertheless, it is reasonable to assume from what we now know that some far more cost effective data networks must be established.

Shortly we will show some examples of recent satellite work that bear out the optimism that this will be done. Before we take up these individual examples, I would like to review about fifteen years of a related development that illustrates the difficulties in the interpretation of remotely sensed data of the ocean surface. The point of this discussion is how an important result can almost be in our grasp but for inadequate support of work on the basic phenomena - in this case the air - sea interaction that generates surface waves.

I am talking about the microwave scatterometer. This is currently a 13 GHz radar which uses the scattering cross-section from the ocean surface to estimate windspeed. There was one in Skylab and there will be a better one on Seasat A. NRL made extensive measurements and found a weak dependence on velocity (Figure 3).

More or less the same data but from different regions plotted log-log shows an apparent dependency (Figure 4).

The next figure shows the scatter in the power dependency on velocity versus angle (Figure 5).

Another plot of this exponent but versus frequency also shows great scatter (Figure 6).

In an attempt to pin down the scatter, a combination of AAFE program and Skylab measurements were analyzed and the results are shown in Figure 7. This shows a scatter of 8 knots which is not very encouraging over the range of 15 to 30 knots displayed. Slide 8 (Figure 8) shows more of similarly obtained data in a different way.

I suppose the point I am trying to make, using this important example, is that the scatter has not been reduced after 10 years of work. First we note that the radar X-section is non-dimensional and therefore some other variable is needed to develop a relation with the windspeed which is dimensional. This is a point emphasized by Klaus Hasselmann. It could be surface tension (which strongly influences the small waves that are responsible for the microwave scatter) or the RMS wave height. In any event, much further support is needed for the oceanic part of the research.

As a counterexample of what can be done by remote sensing using radio waves, I describe experiments designed to measure the growth rate of waves as a function of angle to the wind using downwind observations off a lee shore. The experiments were done at Wake Island in 1972 and Galveston in 1976.

It was in 1956 that Crombie first observed UF scatter from the sea and recognized that it was Bragg scatter. Nevertheless, it wasn't until 1972 that the scatter was normalized by wave measurements at the same time and place (despite about 30 papers in between).

This is a very important field of research; both because of its practical application to remote sensing of the ocean surface in terms of wave height at a distance but also because of its use in measuring the wave spectrum generation, saturation, and angular dependence.

The radio frequencies involved are about 2 to 30 mc/sec and these correspond in wavelength to twice the range of dominant (in terms of energy) wavelengths in the ocean. Just as in the acoustic case discussed earlier, the radio scatter caused by the ocean surface was from WWII and considered only noise and earned the name clutter. It was well enough known that the radar experts had a number -20 db assigned to the value of this dimensionless cross-section (scattering cross-section per unit area of ocean surface).

In first and very good Rayleigh scattering approximation, it can be proved that the scattering x-section goes like k^{-4} . The saturated wave power spectrum goes like k^{+4} in this range. This is known theoretically and experimentally. The product is independent of wavelength and this agrees with the radar observations. The coefficient in the power spectrum even is known reasonably well and it does agree with the -20 db figure.

This is a very exciting result, uniting as it does, two very different phenomenologies. Considerable efforts are being expended to convert this to a genuine remote sensing technology.

It is even possible to go further. Since this is Bragg scattering, the return signal is overdetermined. The specific radio wavelength is scattered by a specific oceanic wavelength. The Doppler gives the ocean wave velocity. However, the ocean gravity wave velocity is determined by a well-known formula. Very often the observed Doppler velocity does not agree with calculated wave velocity and the difference is ascribable to the surface current. This then gives a technique that in principle sense the surface currents.

From among the set of possibilities, I chose illustrations from some experiments on wave development in a fetch.

The slide (Figure 9) is that of the wave buoy that was used for the measurements and is capable of some directional discrimination, as well as for developing the wave height power spectrum. The results that follow are from joint Stanford/Scripps Institution of Oceanography work and the particular experiment was proposed by Robert Stewart of Scripps. The radio signal employed was a 2Mhz Loran signal. This is 160m wavelength and is Bragg scattered from 7 sec ocean waves moving radial to or from the antenna. The antenna itself was transported on a straight section of beach to give a 5 degree synthetic operation. The general layout is shown in Figure 10 (the slide, Figure 10a).

The results are shown in the next slide (Figure 11). They represent five different directions but the cross-sections can be assimilated into one universal curve when plotted versus range times cosine of the angle to the wind direction, the results are very nice. It was Calvin Teague at Stanford who picked up this correlation.

As I said earlier, we would jump from one application to another. This, however, is the nature of the subject - it is not a science but a collection of disciplines working on the oceans. The next one is from geophysics and is the geoidal information obtained from satellites that could be used oceanographically. The first is spectacular and is the result of (Figure 12) comparatively coarse (1m.) altimeter measurements of the surface of the ocean as the satellite sweeps over the regions of the deep oceanic trenches. The anomaly is clearly and quickly shown. The ease is startling compared to the tedious shipboard work of von Arx of Woods Hole Oceanographic Institute that first demonstrated this anomaly.

More important, at least to physical oceanographers, would be results that could interpret ocean heights to 10 cm or better. Unfortunately, this requires an altimeter good to at least this sensitivity. This is instrumentally difficult as well as physically difficult - requiring atmospheric corrections for example. In addition, it requires an equivalent geoid determination for the precision of the satellite motion. This achievement would be fundamental in elucidating the oceanic behavior I described in my opening remarks. The interesting dynamic and static variations in oceanic heights are between 10 cm and 1m.

The theme that runs through most of the examples is the necessity for ground truth of "ocean" truth in oceanic remote sensing - particularly if truth is defined to include a good understanding of the relevant oceanic processes. A very important but rare case is where this ground truth is provided by an earlier long-time series. We have this in the California current system in the region from the tip of Baja to the northern California boundary and seaward to an 80 km grid of stations reaching seaward several hundred miles and in lesser density to Hawaii. This data is part of the CalCOFI measurements made during the last 27 years at one to three month intervals in most years. The time and space grids are generally too coarse for mesoscale analyses but during a number of intervals, such behavior has been observed and agrees with theoretical estimates of similar basis to those made earlier but with appropriately different parameters such as depth and Vaisala frequency.

Given this wealth of data, the California current system has proven to be an almost ideal target for NOAA-3's very high resolution radiometer. It is doubly fortunate because this coast is subject to frequent San Ana conditions where adiabatic dry air from a continental high blows seaward yielding an essentially cloudless condition perfect for observation. The slide shows such a pattern off of point Concepcion - the upper in the visible range, the lower (Figure 13) in the infrared. The range of 10 gray scales is 7 degrees C and the several mesoscale eddies are clearly visible. The next slide is of the waters off of Baja California and the eddy structure is also apparent here. The team led by R. L. Bernstein working on this problem has been able to trace the complete time evolution of one meander to cutoff.

Given these examples, what can be said of the possibility of useful remote sensing from satellites of the oceans below the surface. Bernstein points out that in the case of the California current system there is a historically established connection between the surface and main thermocline temperature distributions. In this case, it is possible to make circulation interpretations although the accuracy would still depend on some available local subsurface measurements.

More impressive is the possibility of using internal wave information as manifested on the surface. The slide shows a spectacular (to an oceanographer at least) example on the shelf off southwestern Africa (Figure 15). The subject of oceanic internal waves is being intensively developed. It could be that such important processes as vertical diffusion can be attributed to the internal wave structure. Unfortunately, to date their surface manifestation have only been observed on the shelves where, of course, they are particularly marked.

There are other possibilities. Stewart has shown experimentally that it is possible to obtain the current shear in the upper layer from the Bragg scattering of radio at different wavelengths. Each wavelength has a different skin depth and hence has a slightly different Doppler shift depending on the velocity shear, as we explained earlier. This quantity can be primary in the air/sea interaction measuring as it does directly the momentum transfer to the ocean by the atmosphere. The reverse would be the use of a two wavelength radiometer to measure the heat flow through the surface of the ocean directly. Developments of this nature would have more than a technical significance because of happenings in the Law of the Sea negotiations. There is a drift in the direction of severely circumscribing the freedom for research in the oceans which, if successful, would drive remote sensing technology very hard. The irony is that at present, the United States is committed to publishing oceanic data promptly. If forced to go the satellite route, this may not be the case! I should say that this was the line used by the Russians in lobbying for freedom for ocean research. However, their political leaders have altered the tune and now support restrictions. I must at least touch on the subject I know and understand the least - polar ice. I did make one summer trip to McMurdo and the South Pole, but I didn't need the trip to appreciate the role that polar ice plays in oceanic processes. This must be the classical example of an intractable non-linear problem. Yet one can only be impressed by the information the glaciologists are obtaining from the satellites. The slide is a good example (Figure 16). Since there are a number of important theories on the relation of the polar caps to the ocean climate, and the atmospheric climate, the satellite would seem to be the preferred way to monitor these theories.

One area we have speculated on a great deal at Scripps is the possible application of satellites to the direct measurement of biological productivity in the earth's oceans. There has been sporadic work in this area based either on the optical properties of chlorophyll or on bioluminescence.

Let me explain why this problem is important. Twenty years ago, the fishery experts estimated the maximum sustainable yield of the world's common fisheries at about 200 million tons a year. This was at a time when these combined fisheries were about 20 million tons a year. In time, the catch increased and the estimate decreased. Today, the world catch is about 80 million tons a year and the estimate of the maximum is put at 100 million tons.

This is a tremendous increase in yield. The catch is equivalent to about a tenth of a pound of protein rich food per person per day in this world. Unfortunately, from our poor estimate of the maximum productivity, this cannot go up and from our past experience in common fisheries, we can pessimistically expect to see this growth reversed.

A sensor system that can monitor the oceans productivity would be a major contribution.

My remarks can be more narrowly construed: Because of the slowness of the Law of the Sea Negotiations, the U.S. along with most other nations of the world has unilaterally proclaimed a 200 mile fishery resource. This was done to conserve these resources which were in danger of serious depletion by foreign fleets. This zone is the richest of any one nation and it is in our best interest to see that it is conservatively treated. Even in this narrow sense, surveillance by satellite would be cost effective compared to the classical Coast Guard cutter approach.

I close my talk at this point because I realize that I have jumped from topic to topic in what must have been a most bewildering fashion. But this is characteristic of oceanic research and development. Man does not live on the ocean in any appreciable numbers and certainly very few are below the surface at any one time. Therefore, these various activities are poorly connected in a political legal or social sense. It is this aspect that has made the Law of

the Sea Negotiations so impossible. There is as yet, no strong enough forcing function to compel agreement among the world's nations. This has also been the difficulty with the preparation of this talk. Nevertheless, I enjoyed the preparation and I hope you did the delivery.

Thank you.

LENGTH SCALE

$$L = D\eta/\omega$$

ω = Coriolus parameter
 D = Depth of fluid
 η = Vaisala frequency

$L \sim 1200$ km in the atmosphere
 $L \sim 130$ km in the oceans

FIGURE 1 (Slide 1)

TIME SCALE

$$T = \frac{2\pi R}{\eta D}$$

R = radius of Earth
 η = Vaisala frequency
 D = Depth of fluid

$T \sim 100$ hr in the atmosphere
 $T \sim 1000$ hr in the oceans

FIGURE 1a (Slide 1a)

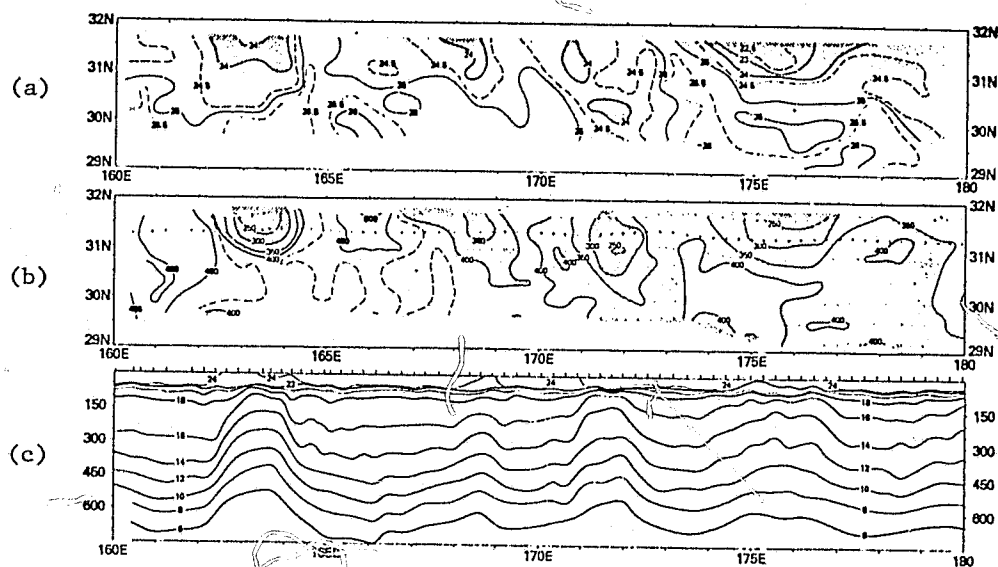
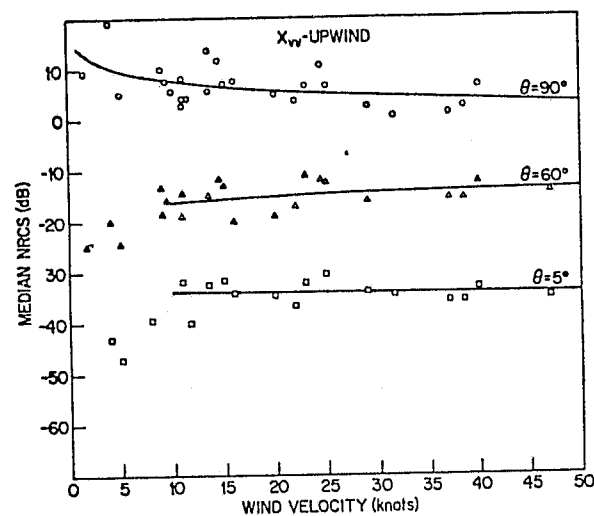


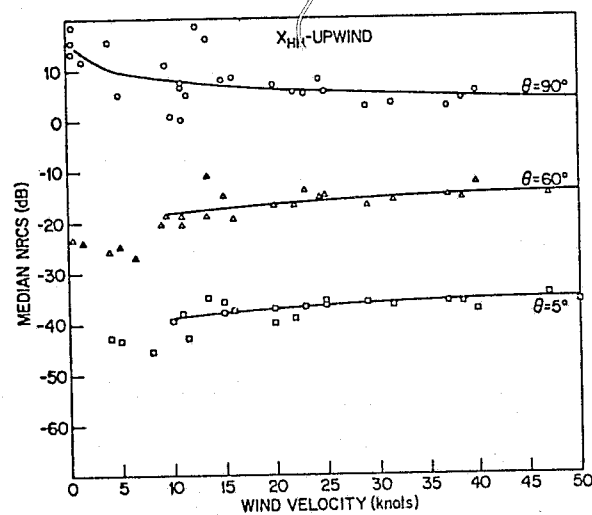
FIGURE 2. EXAMPLES OF OCEANIC VARIABILITY

- (a) Surface temperature in °C (at a depth of 3 m)
 - (b) Depth of 10°C isotherm in meters
 - (c) Vertical section along 3.5° N
- Data taken 3-6 November 1976 by 6 Navy ships steaming along parallel tracks.

From: Wilson, W. S. and Dugan, J. P. 1977 (in press)
Mesoscale Thermal Variability in the Vicinity
of the Kuroshio Extension.



Median NRCS of the sea vs. wind velocity, power law



Median NRCS of the sea vs. wind velocity, power law

FIGURE 3. Shows scatter on data, and difficulty of relating scatter to a unique wind speed

θ Angle from horizontal

NRCS = Normalized radar cross section (per unit area)

From: John Daley, 1973. An empirical sea clutter model
NRL Report 2668.

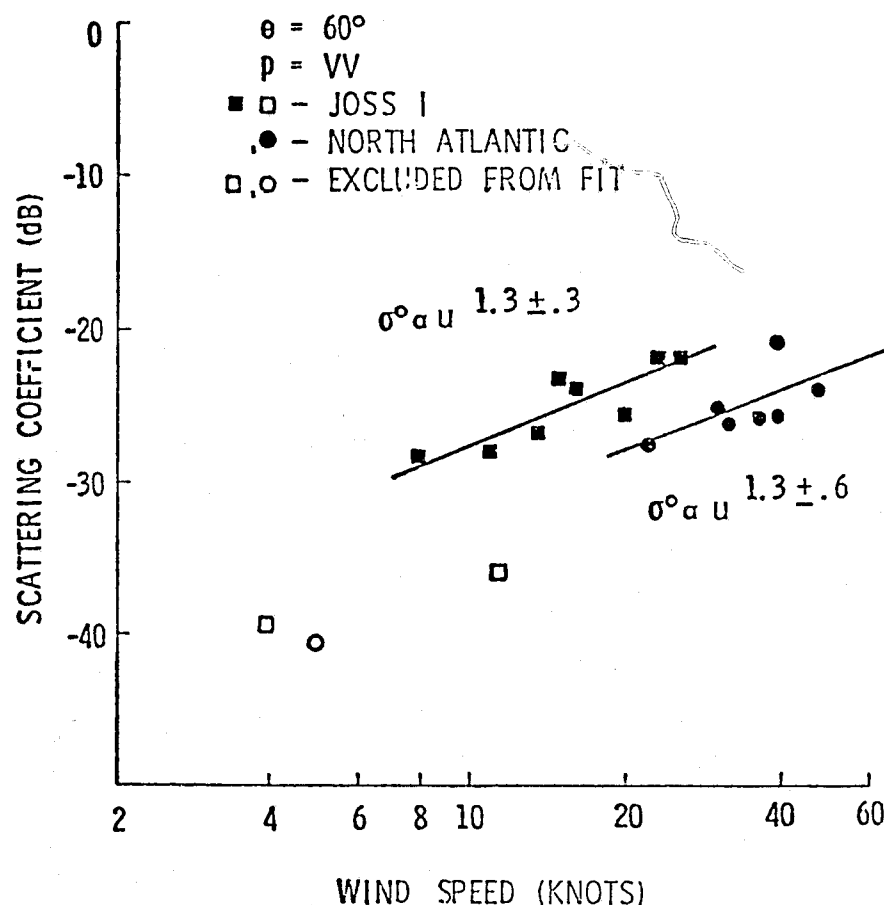


FIGURE 4. University of Kansas power law fits on NRL data by mission.

σ° = radar cross section
 θ = angle from vertical
 μ = wind speed

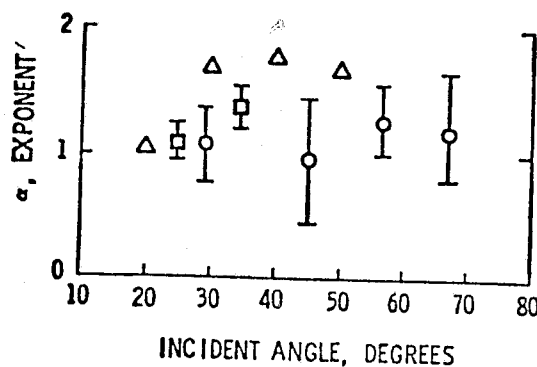
Shows fit of radar cross section $\sim (\text{wind speed})^{\text{power}}$ for two different data sets. NRL claims both sets were well calibrated and difference is real. Kansas claims difference is instrumental.

From: Claassen, J. P. and H. S. Fung, 1972. The wind response of radar sea returns and its implication on wave spectral growth - an opposing view, University of Kansas Tech. Report 186-5.

MODEL: $\sigma^o = KW^\alpha$

where σ^o is scattering coefficient
W is wind speed

○	NRL	8.9 GHz	(3.4cm)
□	NASA/JSC*	13.3 GHz	(2.25cm)
△	AAFE	13.9 GHz	(2.16cm)



Error bars indicate $\pm$ one estimated standard error
(No estimated standard errors are available for the AAFE data)
* NASA/JSC exponents shown are for $\sigma^o(\theta)/\sigma^o(10^\circ) = KW^\alpha$

FIGURE 5. Empirical estimates of the power law relating wind speed and vertically polarized scattering coefficients measured upwind

Plot shows scatter in exponent of correlation between wind speed and radar cross section. All data are very well calibrated, so scatter is not instrumental.

From: Young, J. D., 1976. Active microwave measurements of sea surface winds from space-Appendix D of Cardone (1976) et al.

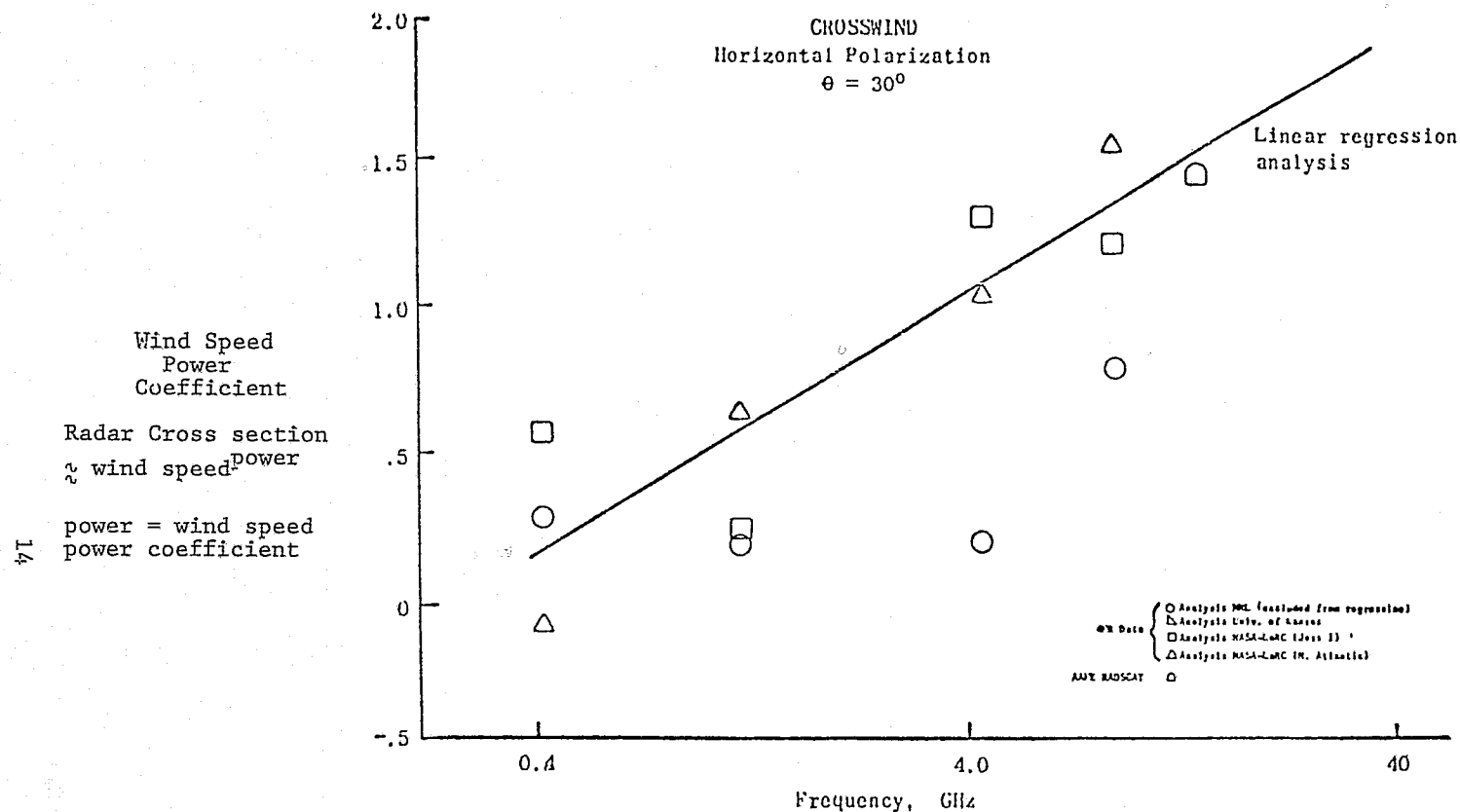


FIGURE 6. Regression analysis; wind speed power coefficient vs frequency

Plot shows scatter in exponent of correlation between radar cross section and wind speed. Data from NRL and NASA programs summarizes all known aircraft data. All are very well calibrated, so scatter is not instrumental.

From: Jones, W. L. and L. C. Schroeder, 1977. Dependence of radar backscatter from the ocean on surface wind speed and direction (in press).

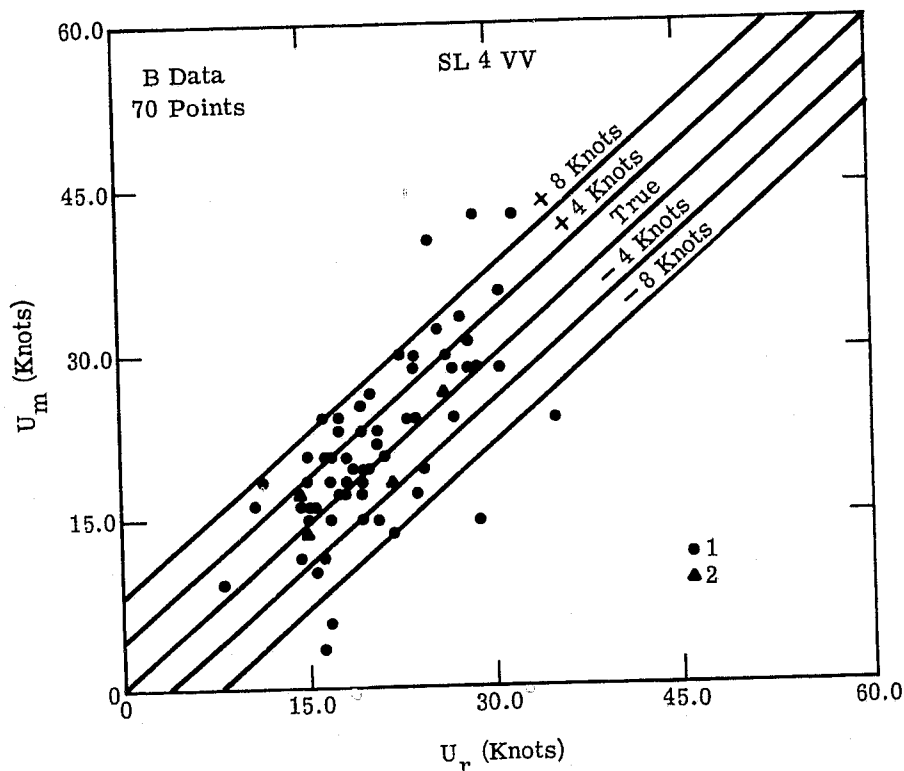


Figure 7a. This plot shows great scatter in radar measured winds when compared with anemometer measurements in scatter area. Scatter is attributed to anemometer by authors, rather than to radar.

50° from vertical - 13.9GHZ (2.16 cm wavelength)
 UV = vertical transmit - vertical receive polarizations
 SL4 = Skylab Mission 4. Analyzed separately because
 antenna was damaged slightly by astronauts.
 U_r = wind observed by radar
 U_m = wind measured by ships with anemometers of
 known height

From: Cardone, V. T., et al., 1976. The measurement of winds near the ocean surface with a radiometer-scatterometer on Skylab. Final report to NASA by University of Kansas/ CUNY Joint Program. Rept. MAS 9-13642.

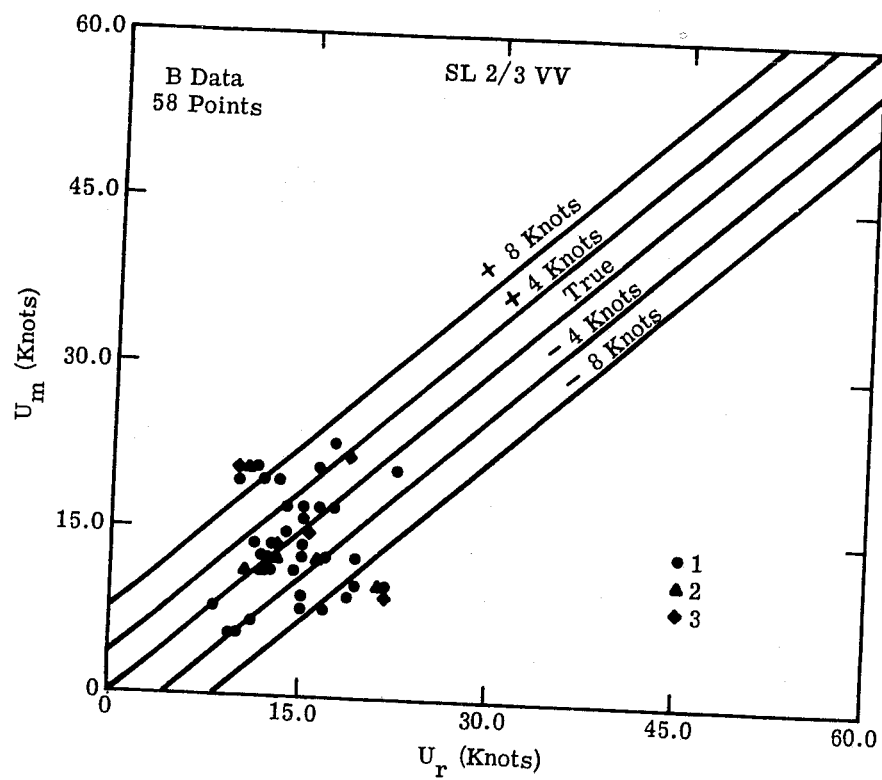


FIGURE 7b. Same as SL4 UV plot, but with different data
 SL 2/3 = data from Skylab Missions 2 & 3.

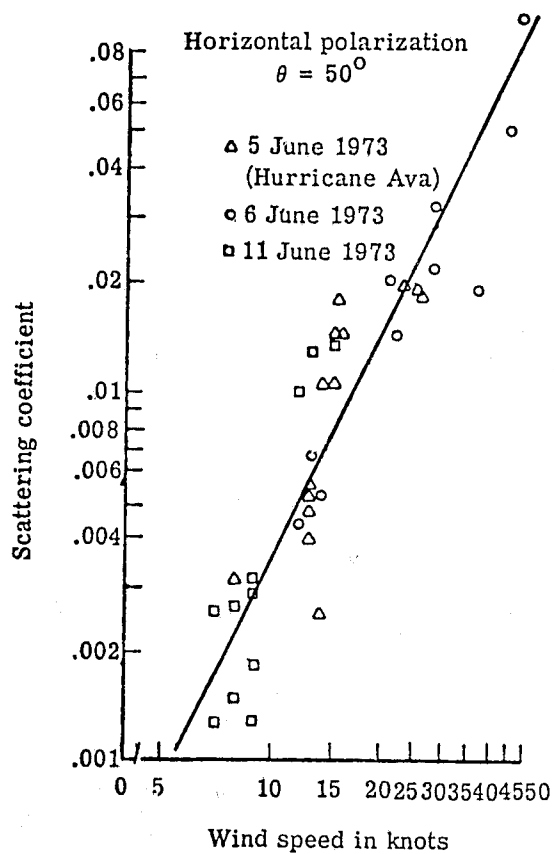


FIGURE 8. Skylab S-193 Scatterometer response to wind at sea (from congressional presentation by Dr. R. K. Moore, Feb. 20, 1974).

Shows scatter in radar observations of wind compared with wind observations or wind calculated from circulation models.

From: Grantham, W. L., et al., 1975. An operational satellite scatterometer for wind vector measurements over the ocean, NASA tech. memo TM X-72672.

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FIGURE 9. Wave Measuring Buoy

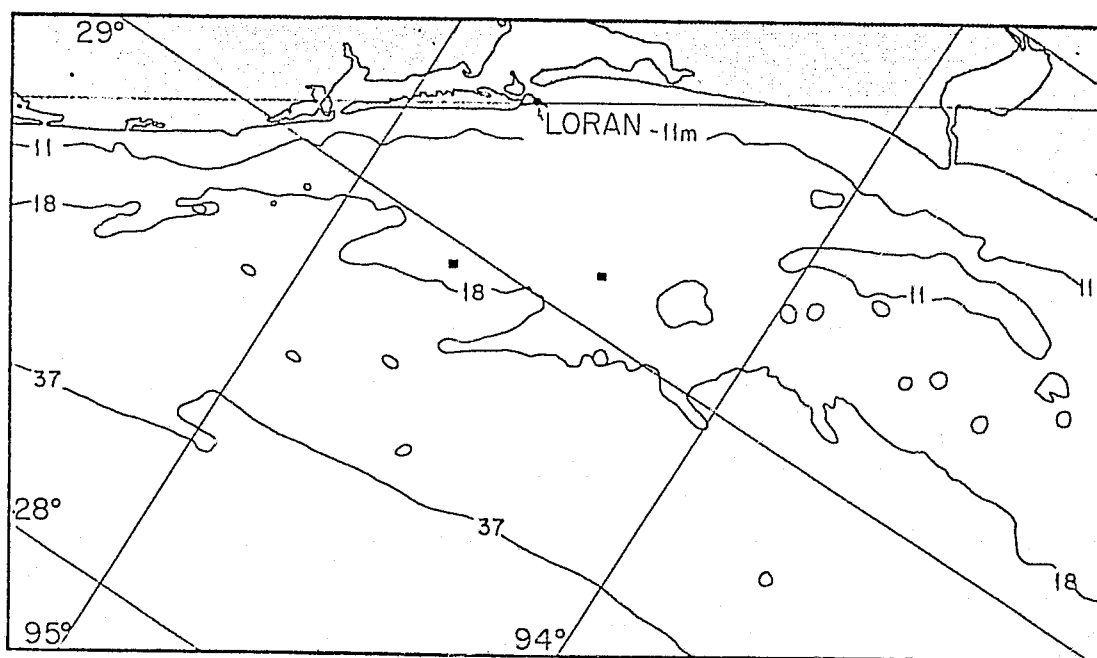
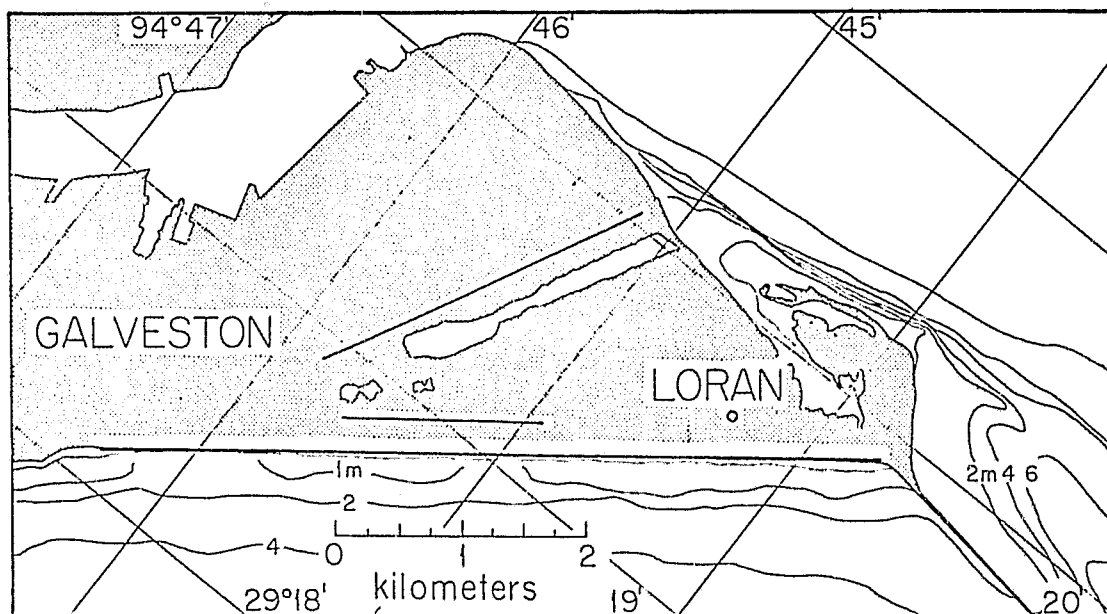


FIGURE 10 (a) and (b) General Layout

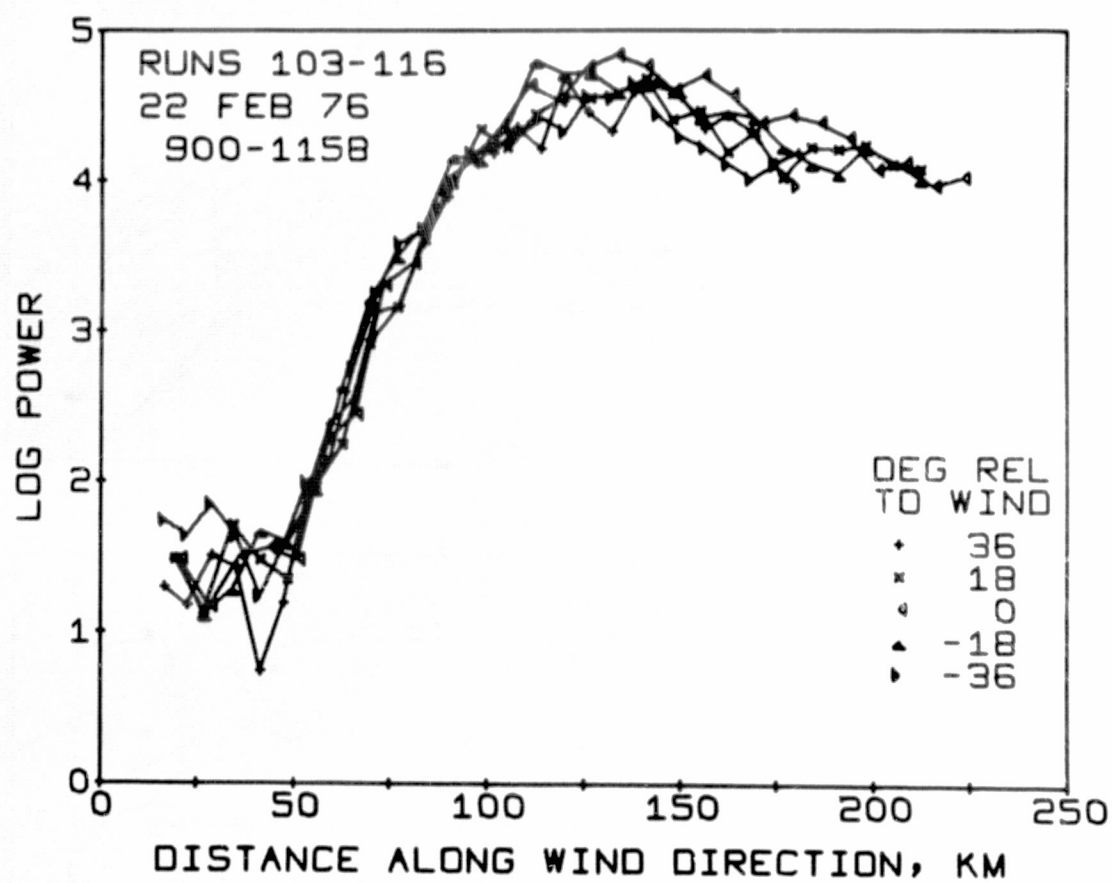


FIGURE 11. Results representing 5 different directions. These cross sections can be assimilated into one universal curve when plotted vs. range times cosine of the angle to the wind direction.

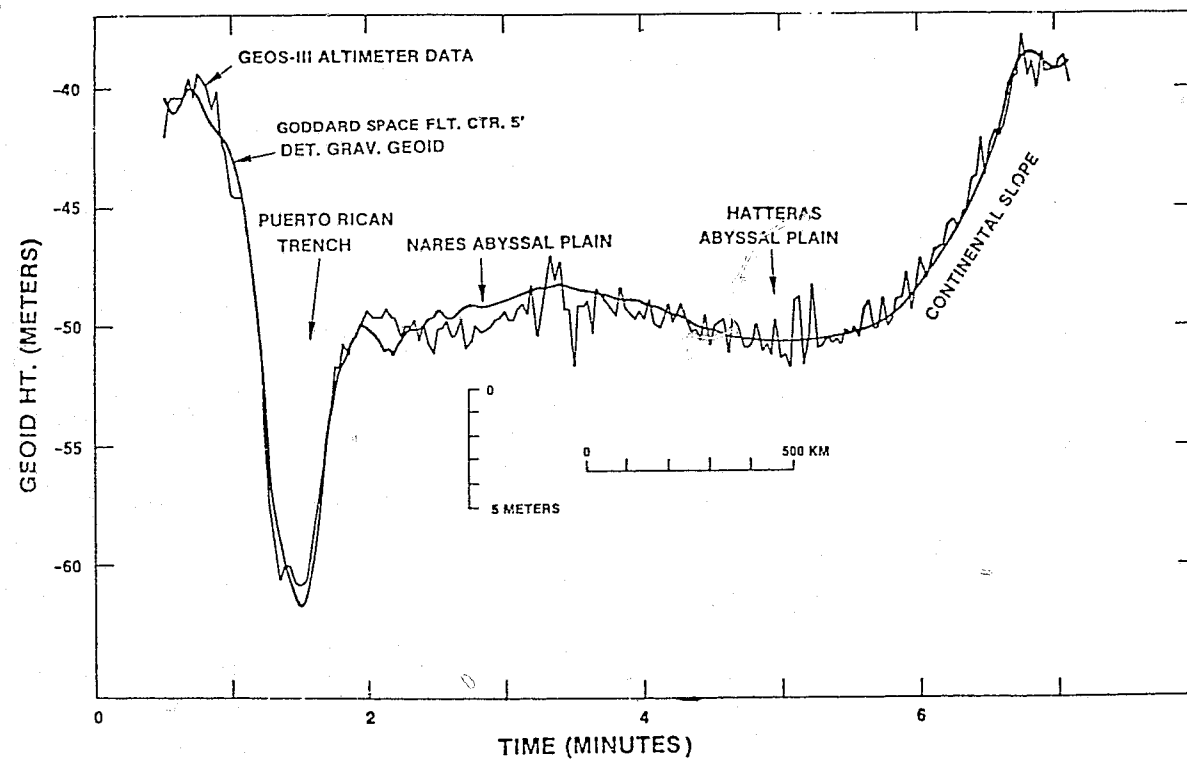


FIGURE 12. GEOS-III Altimeter Pass 260

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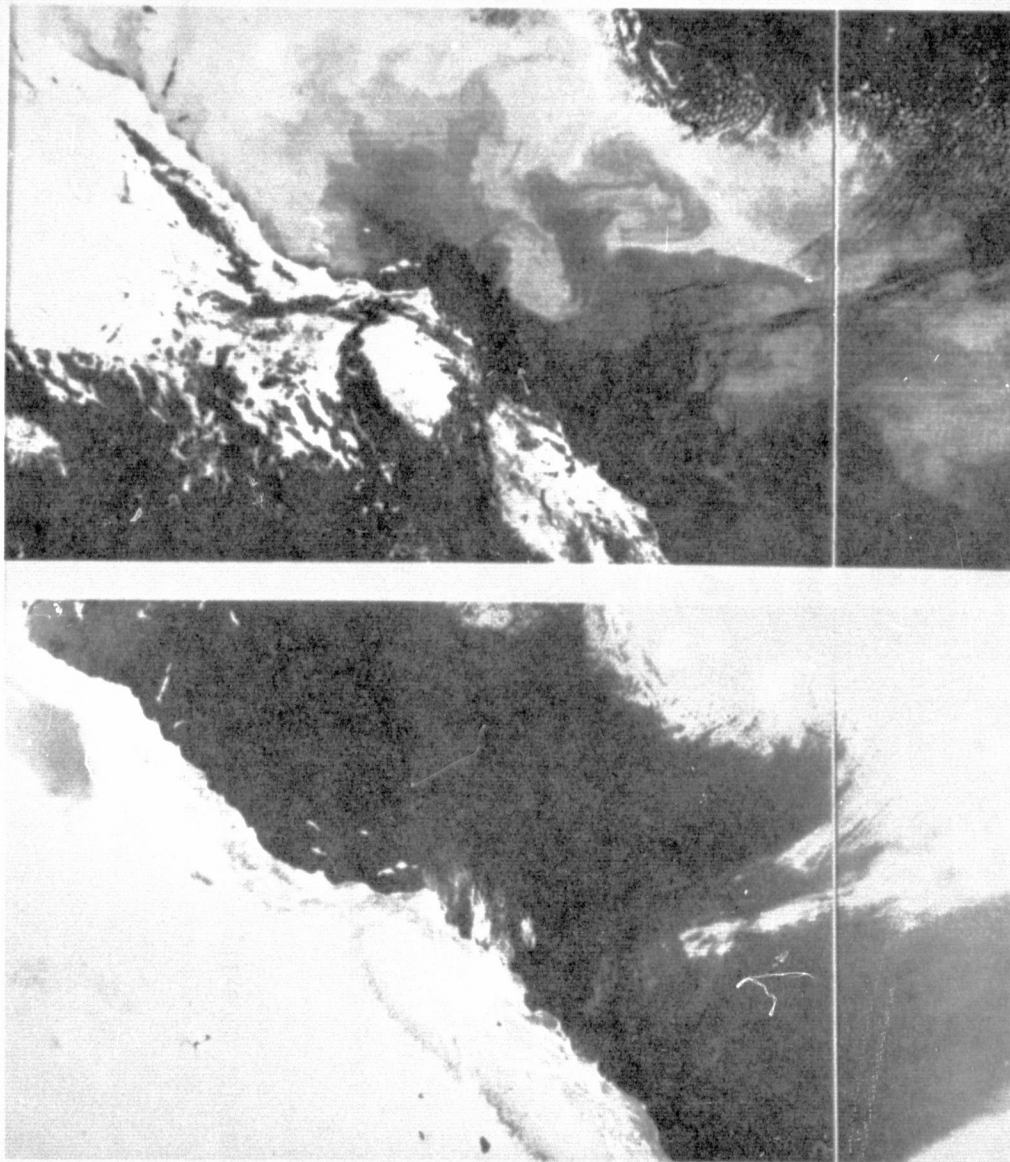


FIGURE 13. NOAA-3 Imagery off Point Conception, California

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FIGURE 14. NOAA-3 Imagery off Baja California

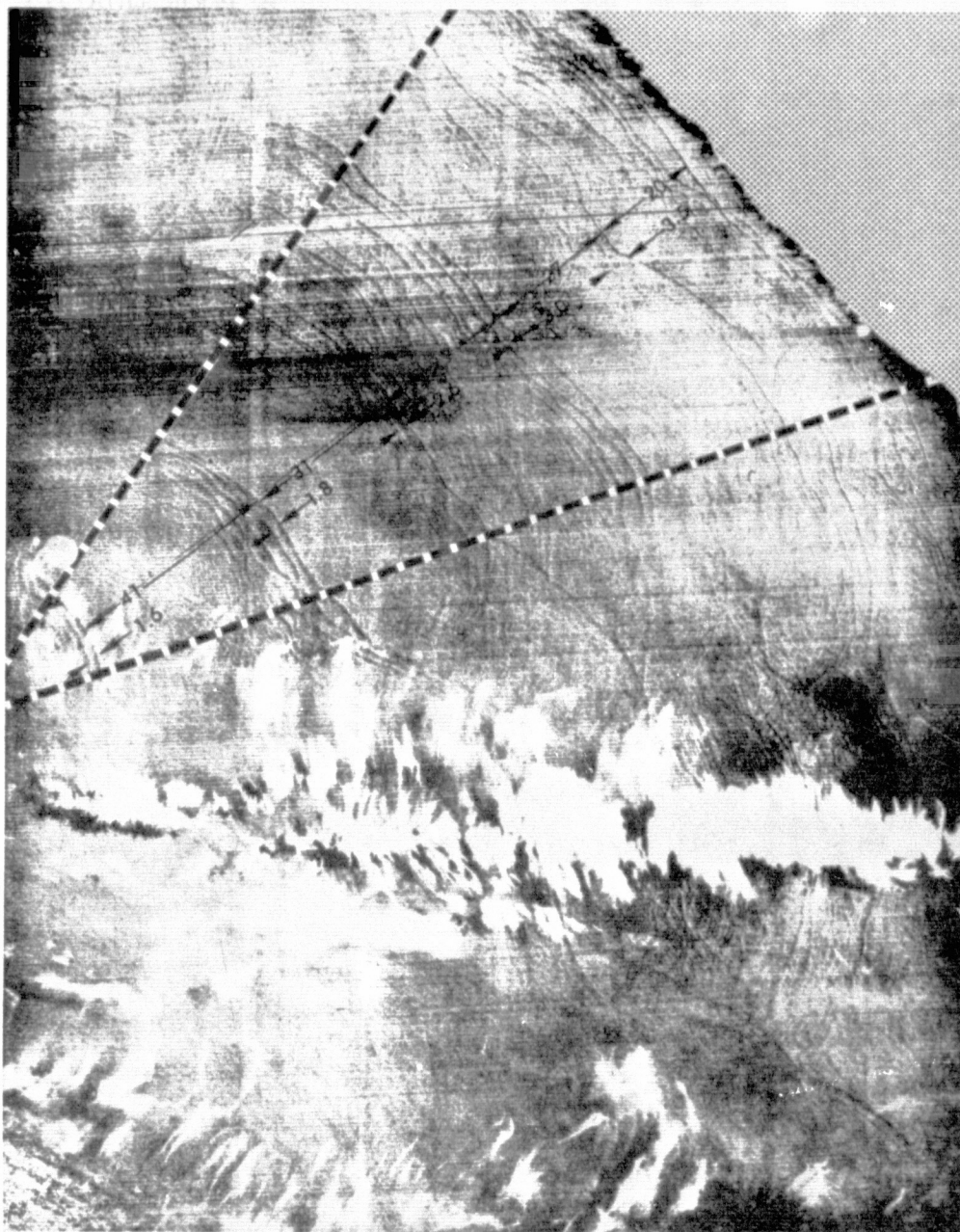


FIGURE 15. Enhanced ERTS photo made on November 28, 1972, off southwest Africa just north of Cape Town, showing six packets of surface slicks apparently radiating from a small source at the center left. This photo suggests internal waves may have lifetimes on the shelf of several days.

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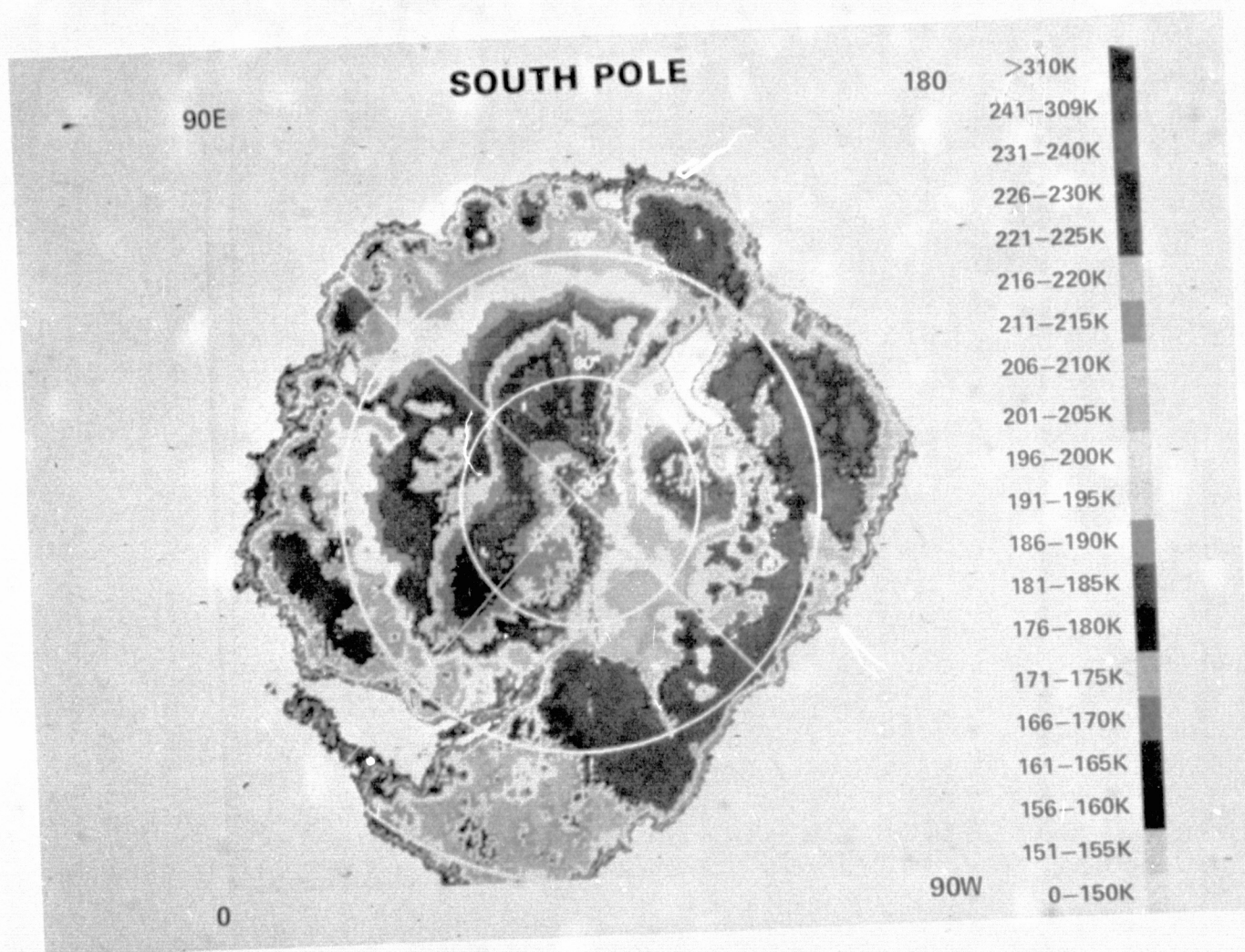


FIGURE 16. False-color polar projection map of 1.55-cm microwave radiometer data obtained on 16-18 December 1972 from the Nimbus 5 satellite in the vicinity of the South Pole. The white area enclosed in the upper right corner of Antarctica is open water in the Ross Sea between the Ross Ice Shelf and the sea ice pack.

OMIT

THE TECHNOLOGICAL RESPONSE

Daniel J. Fink
Vice President and General Manager
General Electric Company - Space Division
Philadelphia, Pennsylvania

When George Zissis invited me to address you today I accepted without hesitation, because it has always been a pleasure for me to participate in this meeting, and to communicate with you who are doing so much to apply science and technology to the important concerns of our time. I also wanted to participate because I feel that we are nearing an exciting transition from experiment to beneficial usage of remote sensing in operational systems, and I wanted to be here to share it with you who have done so much to make it possible.

Although we have been underway for only an hour or so, it is not hard to see concrete evidence that the growth and progress we have come to expect from this meeting have been realized, or perhaps even accelerated.

First evidence is the composition of the attendance. In earlier years, most of those who came here were hardware developers or principal investigators, and we talked mostly about sensing theory, instrument design, and later, data processing. Now I see that with active participation of the user communities, we're beginning more and more to work on the broader task--building the vital bridges between technology and applications.

Then I noted the program itself, which has papers and presentations of far greater technical depth and scope than we have ever had. And instead of concentrating almost exclusively on the interpretation and measurement of discrete phenomena, as in the past, they're evolving into assessments of whole systems and models.

Bill Nierenburg's challenging keynote address is more evidence of this progress. A few years ago, his comments about the accuracy of instrumentation, the delays in processing of data, and the difficulty of erecting accurate user models would probably have been considered unique to the oceanographic discipline. Now we can recognize that these are concerns which are shared by people working in the atmospheric and earth sciences. The advancement of remote sensing is becoming less and less dependent on the solution of narrow individual problems in technique. Today, real progress is measured by advances in our capability for broad operational missions. This requires that we integrate our contributing disciplines and move them forward together.

John Muir may have identified himself as a naturalist rather than a technologist, but today he would feel right at home in this Symposium, because of his well-known observation that in nature, everything is connected to everything else. I believe we now have, or can acquire, the working tools to validate that statement. We can integrate and unify all our efforts to observe, measure, and monitor the earth. And, in time, I expect we will be able to understand and manage its phenomena and resources.

*Presented at the Eleventh International Symposium on Remote Sensing of Environment, Ann Arbor, Michigan, April 25, 1977.

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I am encouraged to believe this by the tremendous technical resources our community has developed, and the encouraging signs that they can be integrated and focussed efficiently in operational systems. To understand where we are, we ought to separate our tasks into two categories: the technical tasks which we have always been able to surmount, once we defined them; and the tasks which grow out of interactions between disciplines and human institutions, surprisingly difficult both to define and resolve.

Let's briefly look at how far we've come in technical sophistication. Just think back to the gee whiz days when we were all so thrilled by the Gemini photos. We saw earth resources phenomena in a broad synoptic view for the first time, and the advantages to map makers and geologists were immediately evident. Our interest then focussed on rather narrow technical questions about the viability of platforms and sensors.

Now we have many platforms, and could go from geosynchronous orbits down to any period and inclination one could want, and they function effectively for periods measured in years. On the immediate horizon are new platforms which will have a design goal of ten years, and which will give sensor pointing accuracy to one hundredth of a degree and stability to 10^{-6} degrees per second. Thus we will acquire not only the continuity and reliability that seemed so difficult only a few years ago, but more accurate and straightforward geometric corrections of image data, which will lighten our data processing burden. In addition, the availability of the Space Shuttle for large payloads and variable periodicity will provide a new degree of mission flexibility--perhaps more than we can effectively utilize to the end of this century.

Another leading technical concern, particularly of this Symposium, has been sensors and whether they would enable us to observe really relevant phenomena. We quickly determined that scanner information could be made more accurate and disseminated more rapidly than film, and most of you will remember that development of the multispectral scanner for earth resources use began at this University with a study in late 1964. By this time Tiros was flying infrared devices and the Nimbus instrumentation experiments were under way. Our studies and experience led to the four-channel multispectral scanner which has given such spectacular results on Landsat 1 and 2, and we will add a fifth channel in the thermal band which will fly on Landsat C.

Now this scanner has evolved to the thematic mapper which will be flown on Landsat D to give spatial resolution of 30 meters. It will incorporate six or possibly seven spectral bands of higher radiometric sensitivity, requiring a data rate of about 100 megabits per second, almost an order of magnitude increase over the first MSS. Seasat will carry more evidence of sensor sophistication in the form of a synthetic aperture radar with 25-meter resolution. I believe at least two papers in this Symposium will be devoted to various aspects of this instrument. And we are developing or flying other instruments, passive and active, at various points in the spectrum, for radiometry and other measurements.

These platforms and sensors, up to now, have been supported by a varied complex of data operations. These have ranged from near realtime transmission, interpretation and distribution, as in the case of NOAA's weather satellites, to a utilization cycle consuming weeks and months, as in the case of Landsat imagery. But look at what they have enabled us to do! They have supported the multitude of experiments which have brought remote sensing from a tentative and theoretical concept, to a verifiable body of technology, to a valid and usable data base, to the very threshold of fully operational systems--and all in a few short years.

Our experiments have been so responsive to the spirit of free scientific inquiry that they have produced an amazing variety of results, spanning all disciplines. I can recall few branches of technology which have produced so

much valuable material in so short a time, and I salute all who contributed, including perhaps the majority of all who are in this audience.

But I also believe that this achievement has brought us to the threshold of a new era of research in remote sensing--an era in which our R&D support will grow out of an operational base. And we can't build such a base unless an increasing level of experimental effort and resources is devoted to the needs of single-mission systems, such as crop forecasting, which seem to be likely avenues to operational status.

Today we can talk about these operational objectives more confidently than ever before because of the progress we are seeing in another technical realm--data handling, processing and distribution. For example, some user missions require fully processed data within 24 to 48 hours after observation--much faster than we have been able to supply it. But now we are developing parallel pipeline processors which will process up to 80 million bytes per second, which is eight times more than the total output of Landsat D.

For years, data processing was more rapid, more accurate, and above all, cheaper when done on the ground instead of on the spacecraft. Now microprocessor techniques may reverse this principle. We can now postulate an array occupying about one cubic foot and drawing 150 watts of power which could handle over 100 megabits per second, simultaneously formatting, correcting, and processing the output of as many as 25 instruments. It could integrate the output of these instruments so that the data of one can be processed using the data of another, as for example when an infrared spectrometer can correct the output of a scanning radiometer to account for atmospheric effects.

We also have attractive options for borrowing advanced data processing technology from other fields and applying it to remote sensing missions. From X-ray tomography and sonar, for example, we can acquire the high processing rates and immense storage capacities we need for preprocessing of real-time data, and automated extractive operations.

Data distribution, once a challenge, no longer seems so formidable. NASA's Tracking and Data Relay Satellites will be placed in synchronous orbit to collect and relay data transmission from orbiting platforms in real time, eliminating on-board tape recorder storage. The increasing availability and decreasing costs of Domsat communication links make them look very attractive as the primary channels for distributing remote sensing data to users.

Our slow cumbersome data distribution through the physical handling of photographs and tapes provided a barely adequate base for research. During those years, the prospect of putting an interactive data terminal into the hands of every principal user seemed like an impossible dream. We could only imagine the "transparent system" in which the user would simply receive data on demand, without having to be concerned with the equipment that observed, processed, or transmitted it, just as communications users receive their service on demand, without knowing or caring whether it comes over hard wire, microwave net or satellite.

I firmly believe that this is no longer a dream, but an attainable goal for which technology is already available. The reason we don't have it in operation is because of the barriers that are keeping us from developing the user demand necessary to support such advances.

There are three of these barriers, each inhibiting our efforts in an essential function: first, the extraction of usable information from our data base; second, selecting and formatting that information to fit the needs of the user; and third, adapting the users' organization and procedures to use the information most efficiently. Our success in getting over all three of these obstacles will decide whether remote sensing is to fulfill its potential as one

of the most powerful and efficient operational tools ever to be applied to the world's most important concerns, or whether it will dwindle away as just another piece of promising technology which never quite caught up with its application.

I would identify the first, the information extraction barrier, as purely technical. We have come a long way from the naked eyeball of the photo interpreter to the capabilities of computer based extractive systems, such as the Image 100, which promise even higher capability in their next generation.

Nevertheless, the interactive man-machine complex still requires too much participation and decision-making by man at considerable costs in time and money. Furthermore, we still do not know how to isolate and automatically compensate for errors, such as those induced by the atmosphere. I believe our most important technical task, toward which we should direct an appropriate amount of our resources, is to develop logic and architecture which can diminish the role of human inference in extractive processing. We should have as a goal a system which could be operated at the necessary output rates by technicians with moderate skill and experience levels. Our excellent record in overcoming technical barriers should give us high confidence here, especially in view of the availability of data processing advances which I mentioned earlier.

A second area that demands immediate and intense concentration, perhaps because it is almost purely inter-disciplinary, is the development of user models. The user model is usually defined as the algorithm or procedure that translates remote sensing data into a form directly usable by resource managers for decision-making. It is sometimes baffling to see how a thing so easy to define can be so difficult to do--much more difficult than the technical tasks we can define.

I think we're really looking at a physical principle first observed by Alfred Wallace, a contemporary of Darwin. He noted that the distribution of animals seemed to be dictated by relationships between plants, soil, water, and climate in given areas, and that there were both larger numbers of individuals and larger numbers of species at the interfaces where these areas interact. So I like to think that user models are difficult to build simply because they represent interfaces where actions are more complex and varied than those that take place in the domains they connect.

We have come to appreciate this phenomenon in building models for such interdisciplinary processes as food plant growth. Our best model is for corn. Our yield model for wheat, more important in world markets, is only fairly good. On rice and tuber crops, which lead all others in world-wide consumption, we have made very little progress. All of this modeling work uses many sources of information. The most notable attempt to base a model largely on remotely sensed data is LACIE, the wheat crop inventory experiment. Here we have made notable progress, but are just leaving the lower part of the learning curve.

Hydrologists have taken their first steps in using remote sensing to model and predict the water levels in reservoirs. They use Landsat data as land cover maps of drainage basins to predict rainfall run-off or absorption. And the five-day weather forecast is a numerical process in which satellite data on wind speed, temperature, and humidity are used.

It is a safe generalization to say that in all disciplines, the working tools provided by remote sensing are better than the models we are able to build with them. And we must recognize that in many prospective user organizations little is being done, and in others modeling programs are going forward without any remote sensing input or participation. Since the user model must be the bridge between the remote sensing system and the management decisions it is designed to influence, we cannot transfer our rich store of applications technology to the user without it. Therefore, it needs our immediate and intense

concentration along the entire frontier of the user interface. It is a task which demands patience and dedication, as well as thorough technical knowledge.

The third barrier is the institution which must use remote sensing data. Being a human creation, it carries more lags and inertial impediments than the technology which is designed to serve it. So we must exercise our initiative to help each user arrive at institutional arrangements which will shape his operations to our methods and formats. I was interested to read about the Pacific Northwest Regional Commission, composed of the governors of Idaho, Oregon, and Washington along with a federal co-chairman. They formed a task force, with the assistance of NASA and the U.S. Geological Survey, to plan a three-year program using Landsat data for urban land use, agriculture, forestry, range land inventory, and weed control. In the process, they involved 35 separate agencies, and built a training phase into the program to adapt them to use of the Landsat data base.

I cite this group not as a model or prototype, because experience has already taught us that there can be no single type of arrangement which will fit all types of users. What is notable here is that this group of states already had well-developed techniques for land use inventory. But they objectively evaluated the benefits of switching to new techniques based on remote sensing, and they adapted their institutions so as to get the maximum benefits from both the new and the old method.

This kind of initiative resulted from a kind of "demand pull" by a user group which had been well educated about the value and utility of the product, just as in a commercial marketing situation. NASA hopes to see the same kind of action by NOAA and other prospective users of Seasat as validation of spacecraft data progresses.

It seems to me that all prospective users of Landsat data could profitably undergo the adaptation process now, while remote sensing is still on the threshold of the operational stage and thus makes the simplest demands on participating institutions. Those that find value in remote sensing in any of its applications can thus have time enough to make their adaptations through an evolutionary process, growing and changing with their needs and the advances in our capabilities.

Since most of the adaptation to remote sensing methods now seems to be happening in cabinet-level departments of the federal government, the institutional question should also be handled at that level. If governing bodies are formed, they should have as their objectives the advancement and rapid utilization of the remote sensing resource, and not merely its regulation and coordination. However the institutional arrangements are handled, a dominant voice should be given those agencies or bodies which can demonstrate the most benefit from application of remote sensing technology, and which show the most initiative in adopting their operation to its methods and requirements.

It seems to me that improvements in world-wide food production and distribution, if clearly demonstrated as a possibility, would be the most beneficial prospective application for operational remote sensing. NASA and NOAA's LACIE experiment with the Department of Agriculture may provide just such a demonstration. I believe that the DA is thus the leading candidate as the agency first to advance Landsat into fully operational status through this pilot mission. We would be wise to devote whatever resources are necessary and prudent to the support of this thrust.

Briefly then, here is how I see the response of the remote sensing community to the challenges pointed out by our keynote speaker. We have proved conclusively the viability of our platforms and are confident that they can be adapted to any payload, orbit or periodicity requirement we can now foresee. The capability of our sensors has progressed more rapidly than we thought

possible in the days when we had to rely only on cameras and film. But a great deal of work needs to be done, particularly in those interface areas where complex energy interchanges take place, as between the ocean and the atmosphere, and between the atmosphere and the land-mass.

We have shown that a valid data base can be assembled and maintained, but we must adapt the advanced technology now becoming available to our work in high-speed data processing and distribution. We certainly must make the machine assume more of the burden in the man-machine interface which is now at the center of our extractive and interpretive processing. We have integrated many disciplines at least in a primitive way, but must make a better match between system output and user needs through the building and refinement of user models. And we certainly must prepare now to adapt our institutions at the federal, state, and municipal levels so that they can fairly assess and efficiently adapt the advantages that remote sensing offers them.

Some of these tasks have confronted us since the very first day of remote sensing experimentation. Today we are on the threshold of an era in which for the first time we will have the working tools and the understanding to address them properly. We have a steady flow of Metsat data which will continue into the foreseeable future. Landsat 1 and 2 have provided data since 1972, and Landsat C is approved for launch late this year or early next year. Landsat D will follow in 1981, with a back-up vehicle available as an earth resources platform, and Seasat will go on line in 1978.

A short time ago, many of us were concerned because we knew that prospective users saw no guarantee of data continuity. Thus, they were reluctant to invest the time and money necessary to build the bridges toward operational use of remote sensing. Today we have reasonable confidence that for the next ten years, we will not only have a steady flow of data, but that the data will grow in volume and in usefulness to the peoples of the world. We should seize this opportunity and use it to integrate our disciplines and concentrate our resources on the remaining barriers. If we do, we won't have to worry about data flow, because we will create such an expansion in operational adaptations that the user demand for data will become irresistible.

In order to ensure that this opportunity will not be lost to us, we must improve our performance in one more vital area, the area of advocacy. We must remember that the achievements and benefits of the whole remote sensing program, so obvious to all of us, are virtually unknown to many prospective users, to opinion leaders in the community, and to many decision makers in government. Some may be skeptical because, in our early enthusiasm, we talked about these benefits before we could fully document them. What a message we now have to bring to these people! We have a powerful program with proven capability to address world-wide problems in food supply and distribution, new sources of energy, water conservation, improved weather forecasting, land use planning, resource conservation and dozens of other areas. We can demonstrate its cost-effectiveness, not by assigning some arbitrary value to its future benefits, but by showing that it can pay its own way in real dollars and cents. And we have shown that these benefits can be developed on an evolutionary basis, because our technology can be adapted to a multitude of tasks with minimum disturbance to existing institutions and methods.

This is a powerful message, but we haven't done a good job of conveying it to the people who authorize our programs and approve our budgets. The diversity of our interests has provided us with a very broad base of technology, but it also diffused and weakened our influence in Congress, the OMB, and other governments and administrative bodies at every level. Perhaps it's time to speak with a single and influential voice for the interest of the whole space applications community. This is what the Space Science Board has done for the cause of the applied sciences and with notable success. Perhaps their job is easier. The constituency for the large Space Science project is normally well defined and can be articulated by a few eminent individuals.

But if our problem is more difficult, that is not an excuse for not trying. We cannot assume that there is someone out there taking care of us. I wonder how many professional and user organizations and societies are represented by this audience? If each of those could speak with a single strong voice, then perhaps it would be easier for a group such as the Space Application Board to focus our interest. Certainly our community has the talent and dedication to create the necessary organizations and make them effective vehicles for our purpose. If we want our programs to realize their full potential, we must learn to integrate our advocacy as well as our technology.

When we first looked at those Gemini photographs, there was very little civil remote sensing technology, no resource-oriented program, and no funding. All we had were a few people with the imagination to see a promise that remote sensing could be a whole new branch of science. We knew what our first task was--to demonstrate and validate our concept. We did it so convincingly that today we have a program, we have a recognized body of technology, we have funding, and we have a promise that remote sensing can be the most important achievement of the Space Age.

The fulfillment of that promise now depends on whether we can recognize our next task--the integration of our disciplines and the concentration of our resources on the remaining barriers to fully operational systems.

The drive and dedication that has brought us this far came almost exclusively from within, beginning with a few individuals and creating a whole community of enthusiasm and interest. You are that community. We can make remote sensing realize its potential if we show the same spirit in the next few crucial years. It is up to us, just as it always has been. This makes me, as I have always been, fully confident about the outcome.

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SENSING THE EARTH'S ENVIRONMENT FROM SPACE:
USER NEEDS AND TECHNOLOGY OPPORTUNITIES

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ABSTRACT

The economic and social value of monitoring the environment of earth from space has become better understood in the last few years. Demonstrations of the value of remote sensing from space in the areas resource exploration and utilization, operations efficiencies, and avoidance of loss of life or property are a continuing effort by the Office of Applications of the National Aeronautics and Space Administration and its supporting centers. Considerable effort has been expended working in concert with industry, universities, and the operational government agencies to identify specific measurement and data needs for this monitoring process. The results of a number of these studies are coalesced and generalized here. Comparisons are made with existing sensor capabilities and with the trends in the supporting technology. Areas of high benefit in which there is a large gap between the efforts underway and the need are identified. The problems in narrowing these gaps are briefly discussed.

1. INTRODUCTION

Our ability to carry out rapid studies of new space missions for environmental monitoring applications is limited by the accessibility of related past experience and of technology limits. A number of years ago the SEASAT-A Project was evolved into a relatively cost effective mission (low cost per capability carried) by maximizing the use of available and, in many cases, space qualified systems. Sensors, data systems and satellite were all evaluated in relationship to minimizing technical and cost risk. As a result of the success of this approach, the Special Programs Office of the Office of Applications at NASA Headquarters requested that the Jet Propulsion Laboratory undertake an effort to assess our present status in user measurement needs, space and aircraft remote sensor capabilities, data system capabilities, and satellite support capabilities. The Study, Analysis and Planning Office of the Office of Aeronautics and Space Technology supplemented this support to ensure consideration of a broader array of sensor types and a sensitivity to longer ranged development needs. These assessments were to include a catalog of existing capability, a projection of the trends in the technology which limit the capability and simplified nomograph-like design guides which allow quick determination of the relative difficulty of accommodating a particular user measurement need or set of measurement needs. The assessments are in no way complete, but preliminary volumes are now available in each of the four areas (References 1, 2, 3 and 4). This report addresses the portion of the "Sensor Capability Handbook" which evaluates the match between user needs and sensor capabilities.

2. MEASUREMENT NEEDS

Establishing a comprehensive list of measurement needs for environmental monitoring applications turns out to be a relatively complex task. Extensive and continuing personal interview of the type reported on in Reference 1 has aided us in understanding the process by which a user determines what level of capability he will state that he needs. Major problems

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exist in assessing reported needs due to the following syndromes. Syndrome 1: An inability to separate tomorrow's need from today's problem. Typically this takes the form of limiting the horizontal or vertical resolutions requested to the computational capability available rather than to the phenomenological sizes of interest. It also might take the form of specifying the capability for a sensor system in which the user is participating in the development. Syndrome 2: An inability to separate needs from a personal assessment of what capability is available. In this syndrome users omit needs in areas which have been traditionally unmeasurable from space; or they specify their needs relative to a specific capability under flight development. This second direction is taken due to fear that in revealing a more difficult need they may slow down the inertia in the present technology step.

We have supplemented our own individual interactions with a broad user community with a wide range of published or semipublished assessments developed by other agencies. A list of some of the better or at least more recent assessments is included as references 5 through 8. Reference 5 is an official NOAA assessment of ocean oriented measurement needs for a wide range of application and science subdisciplines. Reference 6 is a combined assessment of ice measurement needs from personnel from the USGS (Geological Survey), CRREL (Army Cold Regions Research and Engineering Laboratory), the Canadian Department of the Environment and NASA. Reference 7 is a NASA compilation of user justifications for Landsat D. Reference 8 is a comprehensive assessment of detail earth resource measurement needs carried out for NASA by General Electric Company. A recent NASA Climate Task Force led by NASA Goddard Space Flight Center provides an important additional reference. This NASA climate plan is still in draft form but contains a broad view of climate measurement needs based on broad science community participation.

For convenience the user needs identified in this effort have been divided into four areas - air or atmosphere, sea or hydrosphere, ice or cryosphere, and land or terresphere. There is much parallelism in the classes of benefits of interest in each area and in the types of measurements in each area necessary to attempt attainment of these benefits. The major user subcommunities which benefit from measurements in the four areas are delineated in Table I. Climate, Pollution, Search and Rescue, and part of Research are extremely interconnected between the four areas, both in physics and in funding. The other benefit areas tend to have specialized communities in each area although the need for greater cross understanding is becoming more and more recognized. Each of the four areas also has a parallelism in the measurements needed in that there is also an equivalence or similarity in the techniques used to measure thermal related properties, convective motions, water cycle processes, composition, biological processes, and human activities.

The measurement needs identified in this effort are compared against the sensor types applicable to some form of inference relative to these needs and to our understanding of the funded space capabilities relative to these needs in Tables II, III, IV and V - for atmosphere, ocean, cryosphere and land areas, respectively. Measurements are divided as suggested before, into those involved with radiative, convective or phase change processes in energy exchange or into those involved with composition determinations and with biological and human processes. The measurement needs shown were accumulated from the references stated earlier plus an array of other reports and personal communications too lengthy to cover here. The numbers represent an assessment of the measurement sensitivities which allow differentiation of the phenomena of interest. Both the goal for sensitivity and the value that provides utility to at least one user subcommunity are given. In general, the best capabilities and the minimum useful capabilities tend to go together but it is not universally true. Climate users, for instance, tend to desire small relative accuracy differentiations for parameters of interest but averaging over the largest areas and longest time cycles deemed useful. Accuracy is used to denote an absolute value relative to an often unknown or dubious in situ measurement standard. The ocean temperature standard, for instance, is a thermometer dropped over the side of an often moving ship. Horizontal and vertical resolution is the resolvable footprint necessary to differentiate the spatial dimensions of the environmental phenomena. Temporal repeat attempts to estimate the perishability of the environment phenomena of interest.

Part two of Tables II, III, IV and V addresses the sensing systems which have been theoretically or experimentally identified as able to provide measurements which can be used to infer all or part of the parameter of interest. For instance, temperature (passive infrared), color (passive visible, and surface roughness variations (active microwave) can all be used to infer current boundaries. Current velocity though is inferred through measurement of the size of ocean surface bulges due to Coriolis effects on moving water systems. The specific phenomena actually measured in order to infer the environmental parameters of interest are discussed in Reference 2. For perspective, Table VI has been provided to illustrate the path that there are also families of measurement emphases within each spectral regime. Each of these families has a particular set of sensitivities and resolutions and a spectra plurality

which satisfies its particular need. These particular functional differences are discussed in Reference 2. An understanding of their differences is assumed in much of the following discussion.

Part three of Tables II, III, IV and V addresses our understanding of the expectations in the presently funded space-sensor flight-programs. For the most part the values are those quoted in the program documentation although there are a few changes or omissions. Some of the quoted energy precisions do not appear to be matching up with expectations so some variation is possible in that column. The effective swath is that swath over which the best quoted accuracies apply. Typically this is of the order of $\pm 30^\circ$ from the nadir in cross track scanning sensors in low earth orbit. Beyond those angles atmospheric and surface phenomena distort the signal in ways that are difficult to back out of the analysis. Less is gained from any wider swaths since $\pm 30^\circ$ is also coincidentally over half of the orbit to orbit spacing for that class of orbits. Many capabilities are unspecified. These are of three classes. The first class has some conceptual development but little or no hardware efforts. The second class may be demonstrated or may be only partially identified from aircraft flights but the space development phase has not been undertaken. These two classes are referred to as measurement voids and are discussed in the next section. The third class of omission is measurements which are considered part of the potential of an existing space sensor system but which had inconsistent values for expected values or were too unknown to allow estimation of reasonable expectations until actual flight experience is obtained. Actually many of the quoted values are really in this last category since capability demonstration will not take place until launch.

3. MEASUREMENT VOIDS AND GAPS

Measurement voids are areas of identified measurement need in which no space sensor or, in some cases, no aircraft sensors exist, to our knowledge. The major measurement voids identified from Tables II, III, IV and V are listed in Table VII. The four areas - air, sea, ice and land - are retained separately. In the atmospheric area there have been radar (active microwave) tests which indicate that precipitation rates and flying object location/identification can be accomplished remotely. There is a weak possibility that some of the sensors on SEASAT-A can be used to test this feasibility but at present this is not in the planning for those sensors. A number of ideas exist for a more optimum implementation of these measurements but investment is limited. Surface air temperature and fog or mist visibility measurements are somewhat related in that some form of atmospheric sounding has the best possibility of success. A passive visible, infrared, and microwave sounding sensor presently under development for shuttle implementation has some potential for supplying this information. This is especially true if additional near surface vertical resolution can be obtained by the addition of several extra channels. Active sounding methods also have promise. In fact, the pressure/density profile measurement has been studied in some depth over the past year and proposals for a multiple channel active microwave system are in process. Other active microwave and active infrared implementations also appear feasible but need work. Vertical atmospheric motions are potentially inferable from cloud motion monitoring and from signal path distortions. Ducts as small as tens of meters in size are of interest, but little has been done to develop this base.

Ocean temperature profiles are believed to be obtainable from Raman backscatter of infrared laser outputs. Some preliminary tests by several organizations have been initiated but interpretation is difficult. Estuary and coastal circulations have been identified thermally and with color but velocity, though important, is not addressed. Perhaps we are limited to in situ measurements with data relay, but the importance warrants more study of remote possibilities. Direct measures of ocean evaporation rates do not appear feasible from space but the combination of sea surface temperature, surface air temperature and humidity profile could be used to calculate such a rate. No concepts for identifying from space the geological formations on the ocean bottom appear to have been proposed. Gravity field measurements have some application but horizontal resolution needs to be much better than is obtainable from space. Salinity measurement possibilities have been identified in the 1.4 GHz (L-band) region of the microwave and through sun glitter measurements within the visible regime. Although an L-band radiometer was flown on Skylab it was only partially successful. Major problems exist in validating the salinity sensitivity and in producing large (greater than 10 meter) scanning (at least ± 30 degrees cross track) antennas. Direct measures of current velocities from space are not available. Conceptually currents cause local bulges in the ocean surface due to Coriolis forces on moving systems. The effect falls off as one moves away from the equator but should be directly related to current flow although the relationships may vary for each current location. The SEASAT-A altimeter hopes to provide some insight into measuring the Gulf Stream bulge but an entirely new technique might be needed if resolutions

consistent with allowing ships to ride or avoid all the currents in the world are to be implemented. Location and sizing of special high-hazard ocean waves like tsunamis and freak waves are important goals but little real work has been accomplished on space measurement. Tsunamis are fast moving waves generated from sudden ocean bottom shifts due to earthquakes. A meter height wave in the open ocean can be translated into many meters of height when it reaches a shore. The SEASAT-A altimeter could provide a fortuitous measure of tsunamis but some less random technique is needed. Freak waves are sudden drops in the ocean surface that may be 100 meters or more in depth. They occur off the coast of France, along the coast of Africa near Madagascar and many other places in the world where there is a reputation for sudden mysterious disappearance of ships. Research may produce a good understanding of the combination of wind, wave and current conditions which make their occurrence probable, but some direct measure could have considerably more effect on reducing present yearly losses. Coastal depths and shoreline/shoal movements are important to many coastal industries. Some depth inference is possible from blue/green radiometry and from wave structure modulations in microwave images, but quantification is extremely complex. Laser systems have some promise from space but need considerable development. Turbidity and nutrient availability studies have been carried out with colorimetry but again interpretation is difficult. Space colorimeters like the coastal zone color scanner are not expected to solve this problem, although fortuitous correlations in some local regions will probably be made. A new or improved technique is needed. Active laser systems again may be good for this but local variations may make the choice of a universally-applicable wavelength impossible. Fish and mammal location from space is valuable for yield management and conservation. Some effort has been spent investigating fish oil residues on the surface and the surface wave modulation effects due to large schools of top feeding fish but these are inconclusive and only partial solutions to a limited subset of a larger problem.

Ice temperatures in depth and ice sublimation rate measures have the same problems of accomplishment as ocean temperature in depth and ocean evaporation rates. Again indirect measures might be possible but little effort has expended developing time. The thickness and top and bottom roughness of ice and snow are important to glaciology and hydrology. Preliminary aircraft studies have shown that 1 to 3 GHz altimetry gives a strong second surface signal if the ice does not contain much salt and the range of surface roughness is not too great. Improved technique and space application is needed.

Land temperatures in depth are needed but no space deployable technique is presently available. Evaporation rates are similarly possible from surface/air temperature differences, air humidity profiles, and an understanding of the surface moisture content relative to micro-roughness effects on moisture release but there are a number of missing understandings in that chain. Topsoil transport and crustal bulges or shifts may be obtainable from altimetry but the sensitivities needed (cm) are limited by the masking effect of large surface roughness variations in the signal footprint. Some new thinking is needed. Lake and reservoir depth measurements have similar problems although aircraft L-band efforts have shown some promise. Soil moisture measurement is certainly an area to which great attention has been given. Although several space concepts have been proposed, it is my opinion that they have little chance of providing a good base for understanding and considerable technique development on earth based and aircraft based systems is warranted. Gravity field measurements may be one technique of inferring magma convection. Some gravity field inference can be taken from altimetry measures of the mean ocean surface position. High harmonics are needed though and so far only gravity gradiometry has been posed as a solution. Space deployed extrapolations from aircraft gradiometry show extremely difficult technical problems in implementing large (5m) moving low-torque systems.

Measurement gaps, on the other hand, are related to the never ending quest for more sensitivity to transferred energy, to more spectral sensitivity or a wider range of spectral regimes with measurement capability and to finer spacial or temporal resolution. Such improvement in capability is limited by technology. Figure 1 shows the problem in a general sense. The major sensor subelements are the transmitter (if active), the collector, and the detector. Science determines the ground resolution, signal sensitivity and spectral band width and regime necessary for differentiation. Curves of the type shown in Figure 1 can then be used to translate those science requirements into engineering limits like power required, aperture size, and detector character. Technology growth overlays help understanding of when the needed technologies might be available. Figures of this type including many more limiting parameters, notations of actual capabilities and Outlook for Space* projections are included in Reference 2. These will not be included here but samples of the kind of figures are displayed in the next section.

*Reference 9

4. SENSOR PERFORMANCE TRENDS

In this section an attempt will be made to point out what's flying, what's in development, and what's needed in terms of specific capability from sensor components. The form that these developments are taking will be discussed by other authors in this session. Only four sensor areas will be covered here: Active and passive microwave and active and passive visible and infrared. Other spectrum regimes are discussed in Reference 2 but they have relatively smaller direct application to earth resources investigations.

A summary of the passive microwave radiometer capability status is shown in Table VIII. Frequency range extension is important in that history has always shown the discovery of new sensitivities to previously unmeasurable phenomena during explorations into unexplored areas. In order to identify these sensitivities and optimize their selection, frequency scanning and control of narrower bandwidths are always needed. The discrepancy in the detector frequency suggested as in development is a component as contrasted to system difference. The lower detector noise progression shown is well understood but new developments are needed beyond those shown which eliminate the need for cryogenic cooling. Antenna development trends are illustrated in Figure 2. Mechanical scanning techniques are usually momentum listed. The sizes and scans shown appear to be reasonable practical limits. The reason that these mechanical scans are not just dropped for the phased array system is the present inadequacy in the obtainable radiometric noise sensitivity of the phased array. This needs work.

A summary of the active microwave radiometer capability status is shown in Table IX. Transmitter frequency choices are limited to those available for space deployment by international agreement. Transmitter power limits are less related to frequency or power magnitude capability than to transmitter life. Traveling wave tube (TWT) amplifiers of reasonable power level, by their present nature, wear out much too rapidly and seldom perform in space sensors for more than a year of operating time. Solid state amplifiers are developing but only in L-band or lower frequencies are the power levels sufficient for space application. Nanosecond pulse capability in space is tied to the transmitter since as pulse length goes down the emitted peak power has to go up to retain a similar signal to noise ratio. Collector and emitter developments are primarily related to size and scan. Imaging radar demands to 100 to 200 m phased arrays are the most demanding trend. Scanning, squinting, and multiple-antenna multiple-frequency implementations make for antenna forms of horrifying complexity. Figure 3 shows some of the illumination possibilities from discussions in Reference 2. Detector developments are related to the microwave radiometers. The major data processing support problem is keyed to the fine resolution potential of the synthetic aperture imaging radars. Data rates in the 2 to 6 gigabit per second range and real time information extraction from such rates are challenges of our times.

A summary of the passive visible and infrared radiometers capability status is provided in Table X. Extensions to the millimeter regime of the far infrared and improvements in the spectral resolving power are needed to allow an improved array of absorption bands for atmospheric and compositional sounders. The development of a 25 km surface resolution space spectrometer to allow simultaneous measurement of a large array of spectral bands is very important for atmospheric sounding. A number of techniques appear promising including extrapolation of standard techniques for spectral separation, use of laser heterodyning, and use of solid state arrays shows some promise for finer resolution and more channels, cryogenic temperatures and in the control of sensor noise. The finer resolution feature imagers have the same potential for gigabit per second telemetry rates discussed in relation to the synthetic aperture radar.

A summary of the active visible and infrared sensor capability status is shown in Table XI. Recent work implies that the range of lasing devices can be extended from the millimeter range to the x-ray range. The millimeter range laser might be particularly interesting if the present radar efforts produce a comparable device at the same frequency. Transmitter power demands provide the limit for space application. Collector developments are generally shadowed by the power demand. Absorption coefficient detectabilities from standard techniques are similar to that shown as flying. The in-development figure for detectability is related to laser heterodyne techniques. New capability is needed to obtain the needed values. Continuous wave laser systems are relatively new and appear to have tremendous potential in the atmospheric composition arena.

5. POST MORTUM

This discussion of user needs and measurement trends has been necessarily abbreviated and is offered as a stimulus rather than an end. The NASA Space Applications Programs are

dynamic entities meant to serve the industrial, agency, and scientific communities. JPL has been blessed with an active role in helping NASA Headquarters with its responsibility to aid the user community in applying new technology to age old earth problems. We welcome interfaces with any of you who have ideas on how some of the problems I have posed might be solved.

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TABLE I. USER SUBCOMMUNITIES USING REMOTE SENSING DATA

ENVIRONMENT BENEFIT	AIR	SEA	ICE	LAND
VIABILITY OF LIFE	CLIMATE FORECASTS			
	POLLUTION MONITORING			
OPERATIONS EFFICIENCIES	WEATHER FORECASTS	SEA STATE FORECASTS	ICE FORECASTS	LAND MOTION FORECASTS
	PLANE SURVEILLANCE	SHIP SURVEILLANCE	LEAD SURVEILLANCE	
HAZARD AVOIDANCE/ ACCOMMODATION	RAIN, WIND & DUST STORM FORECASTS	FREAK WAVE FORECASTS	ICEBERG & FREEZE ONSET FORECASTS	ICING, EARTHQUAKE, & ERUPTION FORECASTS
	SEARCH & RESCUE			
MINERAL RESOURCE MANAGEMENT		MINERAL LOCATION		MINERAL LOCATION
		UTILIZATION MONITORING		UTILIZATION MONITORING
BIOLOGICAL RESOURCE MANAGEMENT (ANIMAL & VEGETABLE)		LOCATION & GROWTH STATUS MONITORING		LOCATION & GROWTH STATUS MONITORING
		YIELD FORECASTS		YIELD FORECASTS
		UTILIZATION MONITORING		UTILIZATION MONITORING
RESEARCH	INTERNAL MACRO/MICROPROCESSES			
	INTERFACE EXCHANGE PROCESSES			

TABLE II. COMPARISON OF ATMOSPHERE MEASUREMENT NEEDS AND FUNDED CAPABILITIES

Environmental Parameter	Differentiation Sensitivities Needed (Goal/Minimum-Useful)					Applicable Sensors					Funded Space Capability							Remarks
	Measurement Accuracy	Measurement Precision	Vertical Resolution	Horizontal Resolution	Temporal Repeat	Microwave		Visible and Infrared		Other	Satellite	Energy Precision	Spectral Channels	Horizontal Resolution	Vertical Resolution	Effective Swath		
						Active	Passive	Active	Passive									
Thermal Balance																		
Surface Air Temperature	0.5/1°C	0.1/0.25°C	--	10/500 km	3/24 hr			*	*		--	--	--	--	--	--	6m Reference	
Vertical Temperature Profile	0.5/2°C	0.1/0.25°C	1 km/5 km	1 km/25 km	3/12 hr		**		**		TIROS-N	1.5°C	20V&IR, 2 μ w	25 km	2 km	1500 km	Combined necessary	
Atmospheric/Cloud Albedo	0.2/4%	0.2/4%	--	10/500 km	3/12 hr				**		NIMBUS-G	1%	12(0.2-50 μ m)	--	--	--		
Atmospheric Heat Flux	0.2/1%	0.2/1%	--	10/500 km	3/12 hr				**		NIMBUS-G	1%	12(0.2-50 μ m)	--	--	--		
Solar Input Heat Flux	10/25 w/m ²	10/25 w/m ²	--	500 km	3/24 hr				**	UV	NIMBUS-G	0.02/0.8 w/m ²	10(0.2-4 μ m)	--	--	--		
Convective Balance																		
Sea Surface Pressure	1/3 mb	1/3 mb	--	1/500 km	3/12 hr	*		*			--	--	--	--	--	--		
Vertical Pressure Profile	1/3 mb	1/3 mb	1 km/5 km	1/25 km	3/12 hr	*		*			--	--	--	--	--	--		
Sea Surface Wind-Velocity/Direction	1/4 m/s, 10/25°	0.5 m/s/20°, 2/10°	--	5/500 km	3/12 hr	**	*				SEASAT-A	2 m/s or 10°, 20°	Ke-Band	50 km	--	1100 km	19m Reference	
Vertical Wind Profile-Velocity/Direction	1/4 m/s, 10/25°	0.5 m/s/20°, 2/10°	1 km/5 km	5/500 km	2/12 hr	*	*		**		GOES-1,2	2 m/s	Visible	25 km	--	--		
Vertical Convective Ducts	10%	10%	10 levels	10/50 km	3/12 hr						--	--	--	--	--	--		
Atmospheric Stability					3/12 hr						--	--	--	--	--	--		
Water Balance																		
Vertical Water Profile	7/30%	7/30%	1/5 km	1/500 km	3/12 hr		**		**		TIROS-N	20%	20V&IR, 2 μ w	25 km	2 km	1500 km	Continued	
Cloud Extent	5/20%	5/20%	--	1/50 km	3/12 hr				**		TIROS-N	1 km	2V, 3 IR	1 km	--	1500 km		
Cloud Level/Thickness	1/5 km	1/5 km	1/5 km	1/50 km	3/12 hr	*	*	*	*		--	--	--	--	--	--		
Precipitable Water	10/50 mg/cm ²	10/50 mg/cm ²	1/5 km	5/500 km	3/24 hr	*	*	*	*		--	--	--	--	--	--		
Precipitation Rate	0.1/2 cm/hr	0.1/1 cm/hr	--	5/500 km	3/24 hr	*	*	*	*		--	--	--	--	--	--	Continued	
Fog/Mist Visibility	10/4 levels		--	1/10 km	3/12 hr		*		*		--	--	--	--	--	--		
Composition																		
CO ₂	0.5/10 ppm	0.5/10 ppm	1/5 km	5/500 km	12 hr/30 days			*	**		NIMBUS-G	0.006 w/m ² str	13-17 μ m	--	1.5 km	Limb		
Ozone	0.01/0.02 cm	0.01/0.02 cm	1/5 km	5/500 km	12 hr/30 days			*	**		SAGE	0.001 sun	0.4-0.8 μ m	200 km	0.1 km	Limb		
CFM ₆	0.1/0.3 ppb	0.1/0.3 ppb	1/5 km	5/500 km	12 hr/30 days			*	*		--	--	--	--	--	--		
NO _x	0.01/0.03 ppm	0.01/0.03 ppm	1/5 km	5/500 km	3 hr/30 days			*	*		SAGE	0.001 sun	0.4-0.8 μ m	200 km	0.1 km	Limb		
CH ₄	0.05/0.15 ppm	0.05/0.15 ppm	1/5 km	5/500 km	3 hr/30 days			*	**		NIMBUS-G	0.003 w/m ² str	3.4, 8.6-9.1 μ m	--	4 km	Limb		
NH ₃	2 x 10 ⁻⁴ / 10 ⁻³ nm	2 x 10 ⁻⁴ / 10 ⁻³ nm	1/5 km	5/500 km	3 hr/30 days			*	*		--	--	3, 10.6, 11.4 μ m	--	--	--		
HNO ₃	0.5/2 ppb	0.5/2 ppb	1/5 km	5/500 km	3 hr/30 days			*	**		NIMBUS-G	0.003 w/m ² str	11.5 μ m	--	1.5 km	Limb		
Aerosols	0.002/0.02 ppm	0.002/0.02 ppm	1/5 km	5/500 km	3 hr/30 days			*	*		SAGE	0.001 sun	0.4-0.8 μ m	200 km	0.1 km	Limb		
SO ₂ , H ₂ S	0.001/0.01 ppm	0.001/0.01 ppm	1/5 km	5/500 km	3 hr/30 days			*	*		--	--	4, 7.4 μ m	--	--	--		
C _x H _x	0.001/0.01 ppm	0.001/0.01 ppm	1/5 km	5/500 km	3 hr/30 days			*	*		--	--	3.3, 9.5-11 μ m	--	--	--		
CO	0.001/0.1 ppm	0.001/0.1 ppm	1/5 km	5/500 km	3 hr/30 days			*	**		--	--	4.8 μ m	--	--	--		
Monitor																		
Airplane/Balloon/Flock/ Swarm Location/Identification	5/100 m	5/100 m	--	0.1/1 km	1/3 hr	*					--	--	--	--	--	--		

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TABLE III. COMARISON OF OCEAN MEASUREMENT NEEDS AND FUNDED CAPABILITIES

Environmental Parameter	Differentiation Sensitivities Needed (Goal/Minimum Useful)					Applicable Sensors				Other	Funded Space Capability						Remarks
						Microwave		Visible and Infrared			Satellite	Energy Precision	Spectral Channels	Vertical Resolution	Horizontal Resolution	Effective Swath	
	Measurement Accuracy	Measurement Precision	Vertical Resolution	Horizontal Resolution	Temporal Repeat	Active	Passive	Active	Passive								
Thermal Balance																	
Sea Surface Temperature-Global	0.2/1°C	0.1/0.25°C	---	50/500 km	3 hr/4 days		**		*		SEASAT-A	0.5°C	5 w	---	121 km	638 km	All weather
Sea Surface Temperature-Local	0.5/1°C	0.1/0.5°C	---	0.25/25km	3 hr/4 days		*		**		TIROS-N+	0.25°C	2V, 3 IR	---	10 km	1500 km	Clear weather
Ocean Temperature in Depth	0.2/2°C	0.1/1°C	2/10 m	10/100 km	12 hr/3 days	*		*			---	---	---	---	---	---	
Ocean Albedo	0.2/1%	0.2/1%	---	25/500 km	3 hr/30 days		*		*		NIMBUS-G	1%	12(0.2-50 μm)	---	---	---	
Ocean Heat Flux	0.25/4 w/m ²	0.25/4 w/m ²	---	25/500 km	3 hr/30 days		*		*		NIMBUS-G	1%	12(0.2-50 μm)	---	---	---	
Evaporation Rate	0.5/2 mm/deg	0.5/2 mm/deg	---	25/500 km	3 hr/4 days						---	---	---	---	---	---	
Convective Balance																	
Wind Shear	0.1/0.3 dyne/cm ²	0.1/0.3 dyne/cm ²	---	5/200 km	3/12 hr	**	*				SEASAT-A	0.2 dyn/cm ²	Ke-Band	---	50 km	1100 km	
Gravity Waves-Height	0.3/0.7 m or 10%	0.3/0.7 m or 10%	0.3/0.7 m or 10%	1/100 km	3/12 hr	**		*			SEASAT-A	0.5 m or 10%	Ke-Band	0.5 m or 10%	2-12 km	Nadir	
Gravity Waves-Length	5/15%, 10/45°	5/15%, 5/30°	---	1/100 km	3/12 hr	**		*			SEASAT-A	10%, 15°	L-Band	---	25 m	100 km	
Wind-Surge/Surface-Transport	1/10 cm, 0.2/1 cm/s	1/10 cm, 0.2/1 cm/s	1/10 cm	500 m/100 km	3/1 month	**		*			SEASAT-A	10 cm	Ke-Band	---	2-12 km	Nadir	
Upwelling Location/Extent	100 m/10 km	100 m/10 km	---	100 m/10 km		**			*		SEASAT-A	25 m	L-Band	---	25 m	100 km	
Ocean Current-Velocity	2/50 cm/s	1/5 cm/s	---	500 m/10 km	3 hr/1 month	**				Buoy Relay	SEASAT-A	10 cm bulge	Ke-Band	---	2-12 km	Nadir	
Ocean Current-Extent/Direction	500 m/10 km, 10°	500 m/10 km, 5/10°	---	500 m/10 km	3 hr/5 days	**		*			SEASAT-A	25 m	L-Band	---	25 m	100 km	
Estuary Circulation-Velocity/Direction	1/5 cm/s, 10°	1/5 cm/s, 5/10°	---	100 m/1 km	3 hr/1 day	**		*			---	---	---	---	---	---	
Fresh Water Influx-Extent/Direction	500 m/10 km, 10°	500 m/10 km, 5/10°	---	500 m/10 km	12 hr/30 days	*	*		**		NIMBUS-G	---	Glitter	---	825 m	1500 km	
Sediment Transport-Extent/Direction	10 m/1 km, 10°	10 m/1 km, 5/10°	---	10 m/1 km	3 hr/5 days				**		NIMBUS-G	0.4%	Yellow	---	825 m	1500 km	
Iceberg Location/Sizing	5/25 m	5/25 m	---	0.5/2 km	12/24 hr	**					SEASAT-A	25 m	L-Band	---	25 m	100 km	
Astronomical Tides	1/10 cm	1/10 cm	1/10 cm	500 m/100 km	3/6 hr	**		*			SEASAT-A	10 cm	Ke-Band	10 cm	2-12 km	Nadir	
Coastal Depth	15 cm/10 m	15 cm/10 m	15 cm/10 m		1/30 days	*		*	*		---	---	---	---	---	---	
Shoal/Shoreline Movements	2/25 m	1/10 m	---	1/10 m	1/7 days	*		*	*		---	---	---	---	---	---	
Marine Geoid	1/10 cm	1/10 cm	1/10 cm	500 m/100 km	3/6 hr	**		*			SEASAT-A	10 cm	Ke-Band	10 cm	2-12 km	Nadir	
Biological Balance																	
Surface Salinity	0.01/1 ppt	0.005/1 ppt	---	1/200 km	12 hr/30 days		*		**		NIMBUS-G	0.4%	0.55 μ (yellow)	---	825 m	1500 km	
Turbidity	0.01	0.01	---	100 m/1 km	6/12 hr			*	*		---	---	---	---	---	---	
Nutrient Availability			---	100 m/1 km	12 hr/3 days			*	*		---	---	---	---	---	---	
Chlorophyll Extent/Concentration	0.3 μg/l or 10%	0.3 μg/l or 10%	---	100 m/1 km	12 hr/3 days			*	**		NIMBUS-G	0.4%	0.44, 0.52 0.67 μm	---	825 m	1500 km	
Vegetation Extent/Type			---	100 m/1 km	12 hr/			*	**		NIMBUS-G	0.4%	0.75 μm	---	825 m	1500 km	
Disease Vectors (e.g. Red Tide, etc.)			---	100 m/1 km	12 hr/			*	**		---	---	---	---	---	---	
Fish/Mammal Location/Extent			---			*	*	*	*		---	---	---	---	---	---	
Fish Oil/Biproduets			---			*	*	*	*		---	---	---	---	---	---	
Human Impact			---			*		*	**		NIMBUS-G	0.4%	V&IR	---	825 m	1500 km	
Pollutant Extent/Identification			---			*		*	**		SEASAT-A	25 m	L-Band	---	25 m	100 km	
Ship Location/Identification	1 m/100 m	1 m/100 m	---	30 m/2 km	3/12 hr	**					SEASAT-A	25 m	L-Band	---	25 m	100 km	

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TABLE IV. COMPARISON OF CRYOSPHERE MEASUREMENT NEEDS AND FUNDED CAPABILITIES

Environmental Parameter	Differentiation Sensitivities Needed (Goal/Minimum-Useful)					Applicable Sensors				Other	Funded Space Capability						Remarks
						Microwave		Visible and Infrared			Satellite	Energy Precision	Spectral Channels	Horizontal Resolution	Vertical Resolution	Effective Swath	
	Measurement Accuracy	Measurement Precision	Vertical Resolution	Horizontal Resolution	Temporal Report	Active	Passive	Active	Passive								
Thermal Balance																	
Surface Temperature	0.5/1°C	0.1/0.25°C	--	5m/500 km	3 hr/4 days		*		**		TIROS-N	0.25°C	2V, 3 IR	10 km	--	1500 km	
Temperature in Depth	0.5/1°C	0.1/0.25°C	--	5m/25 km	12 hr/30 days						--	--	--	--	--	--	
Surface Heat Flux	0.25/4 w/m ²	0.25/4 w/m ²	2/10m	100m/500 km	3 hr/30 days				**		NIMBUS-G	1%	12(0.2-50 μm)	--	--	--	
Surface Albedo	0.2/1%	0.2/1%	--	100m/500 km	3 hr/30 days				**		NIMBUS-G	1%	12(0.2-50 μm)	--	--	--	
Sublimation Rate	0.5/2 mm/deg	0.5/2 mm/deg	--	25/500 km	3 hr/4 days						--	--	--	--	--	--	
Convective Balance																	
Ice/Snow Extent	5m/25 km, 3%	5m/25 km, 3%		5m/25 km	12/24 hr	**	*	*	*		SEASAT-A	25m	L-Band	25m	--	100 km	
% Open Ocean	3/30%	1/25%	--	0.5/100 km	12 hr/7 days	**	*	*	*		SEASAT-A	25m	L-Band	25m	--	100 km	
% Snow Cover	5/20%	2/20%				**	*	*	*		SEASAT-A	25m	L-Band	25m	--	100 km	
Ice/Snow Thickness	10 cm/5m	10 cm/5m	10 cm/2m	2/50m	12 hr/3 days	*					--	--	--	--	--	--	
Ice/Snow Surface Roughness	10 cm/1m	10 cm/1m	10 cm/1m	1/10m		*	*	*	*		--	--	--	--	--	--	
Ice Drift	5m/25 km	5m/25 km	--	5m/25 km		**					SEASAT-A	25m	L-Band	25m	--	100 km	
Ice Deformation	50/100m/yr, 0.1%	50/100m/yr, 0.1%				**			*		SEASAT-A	25m	L-Band	25m	--	100 km	
Age	1, 2, mult	1, 2, mult	--	2/20 km	12 hr/3 days		**				SEASAT-A	1, 2+ yrs	37 GHz	21 km	--	638 km	
Berg Formation Rate											--	--	--	--	--	--	
Ice Lead/Crevasse Location/Sizing	5/100m	5/100m	--	5/100m	1/6 hr	**			*		SEASAT-A	25m	L-Band	25m	--	100 km	
Human Impact																	
Search & Rescue			--	30m/1 km	3/12 hr					Relay							

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TABLE V. COMPARISON OF LAND MEASUREMENT NEEDS AND FUNDED CAPABILITIES

Environmental Parameter	Differentiation Sensitivities Needed (Goal/Minimum Useful)					Applicable Sensors					Funded Space Capability						Remarks
	Measurement Accuracy	Measurement Precision	Vertical Resolution	Horizontal Resolution	Temporal Repeat	Microwave		Visible and Infrared		Other	Satellite	Energy Precision	Spectral Channels	Horizontal Resolution	Vertical Resolution	Effective Swath	
						Active	Passive	Active	Passive								
Thermal Balance																	
Surface Temperature	0.2/1°C	0.1/0.5°C	--	2/100m			*		**		LANDSAT-D	1°C	IR	30m	--	185km	
Temperature In Depth	0.2/1°C	0.1/0.5°C	10 cm/1m	2/100m							--	--	--	--	--	--	
Surface Heat Flux	0.25/4 w/m ²	0.25/4 w/m ²	--	25/500km					*		NIMBUS-G	1%	12(0.2-50μm)	--	--	--	
Surface Albedo	0.2/1%	0.2/1%	--	25/500km					*		NIMBUS-G	1%	12(0.2-50μm)	--	--	--	
Evaporation Rate	0.5/2 mm/deg	0.5/2 mm/deg	--	25/500km		*	*				--	--	--	--	--	--	
Convective Balance																	
Crustal Shifts			--			**					SEASAT-A	25m	L-Band	25m	--	100 km	
Crustal Bulges	1/10 cm	1/10 cm	--			**		*			SEASAT-A	10 cm	Ke-Band	2-12 km	10 cm	Nadir	
Topsoil Transport			--		1 mo/1 yr	*		*	*		--	--	--	--	--	--	
Volcanic Activity			--			*		*	*		LANDSAT-D	30m	V&IR	30m	--	185km	
Thermal Sources	0.2°C	0.2°C	--	10/130m					*		LANDSAT-D	30m	V&IR	30m	--	185km	
Magma Convection			--			*				Gravimeter	--	--	--	--	--	--	
Water Balance																	
Lake/Reservoir/River/Extent	1/25m	1/25m	--	1/25m		*			**		LANDSAT-D	30m	V&IR	30m	--	185km	
Lake/Reservoir Depth	10 cm/1m	10 cm/1m	10 cm/1m	1/25m		*		*			--	--	--	--	--	--	
Wetlands Extent	2/100m	2/100m	--	2/100m		*			**		LANDSAT-D	30m	V&IR	30m	--	185km	
Soil-Moisture/Irrigation	0.01/0.05 cc/cc	0.01/0.05 cc/cc	--	10m/500 km	3 hr/1 mo	*	*		*		--	--	--	--	--	--	
Mineral Resources																	
Geological Formation Mapping	2/100m	2/100m	--	2/100m		*			**		LANDSAT-D	30m	V&IR	30m	--	185km	
Surface Character/Roughness	2/100m	2/100m	--	2/100m		*			**		LANDSAT-D	30m	V&IR	30m	--	185km	
Mineral Identification/Location	2/100m	2/100m	--	2/100m		*			**		LANDSAT-D	30m	V&IR	30m	--	185km	
Mining/Drilling Land Use	2/100m	2/100m	--			*			**		LANDSAT-D	30m	V&IR	30m	--	185km	
Biological Resources																	
Acid/Base Balance			--								--	--	--	--	--	--	
Nutrient Availability			--						*		LANDSAT-D	?	V&IR	30m	--	185km	
Chlorophyll			--						*		LANDSAT-D	?	V&IR	30m	--	185km	
Vegetation: Extent/Type/Growth-Status	2/5%	2/5%	--	2m/500km	1/7 days	*			*		LANDSAT-D	30m	V&IR	30m	--	185km	
Plant Water Stress			--	10m/500 km	12 hr/1 wk	*			*		LANDSAT-D	30m	V&IR	30m	--	185km	
Disease Vector Extent	2/5%	2/5%	--	10m/500 km	1/7 days	*			*		LANDSAT-D	?	V&IR	30m	--	185km	
Grazing/Range-Hard Effects	2/5%	2/5%	--	10m/500 km	1/7 days	*			*		LANDSAT-D	?	V&IR	30m	--	185km	
Human Impact																	
Water Quality	?	?	--	5/50m					*		LANDSAT-D	?	V&IR	30m	--	185km	
Urban/Power/Transport Land Use			--	5/50m		*			*		LANDSAT-D	30m	V&IR	30m	--	185km	
Search and Rescue			--			*				Relay	--	--	--	--	--	--	
Space Effects																	
Magnetic Field	0.01/100γ	0.01/100γ	--	0.1/0.7 deg	Monthly					Magnetometer	MAGSAT	--	--	--	--	--	
Trapped Particle Field		10/10 ⁴ /cm ² str kev			Monthly					Particle Detector		--	--	--	--	--	
Gravity Field	0.3/0.1 EU	0.3/0.1 EU	--	--	Yearly					Gradiometer	--	--	--	--	--	--	

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TABLE VI. SENSOR LISTING BY MEASUREMENT FUNCTION

SPECTRAL REGIME	ENERGY MECHANIZATION	MEASUREMENT EMPHASIZED
MICROWAVE	PASSIVE	SURFACE SCANNING ATMOSPHERIC SOUNDING
	ACTIVE	ALTIMETRY SCATTEROMETRY ATMOSPHERIC WATER SOUNDING ATMOSPHERIC PRESSURE SOUNDING FINE RESOLUTION SURFACE IMAGING
VISIBLE AND INFRARED	PASSIVE	THERMAL MAPPING ATMOSPHERIC SOUNDING SURFACE COLORIMETRY ATMOSPHERIC COMPOSITION FINE RESOLUTION SURFACE IMAGING
	ACTIVE	ALTIMETRY SURFACE COLORIMETRY ATMOSPHERIC SOUNDING ATMOSPHERIC COMPOSITION

TABLE VII. MAJOR MEASUREMENT VOIDS FROM SPACE REMOTE SENSING

CONCEPTUAL START ONLY	PRELIMINARY AIRCRAFT TEST
SURFACE AIR TEMPERATURE FOG/MIST VISIBILITY PRESSURE/DENSITY PROFILE VERTICAL ATMOSPHERIC MOTIONS OCEAN TEMPERATURE IN DEPTH EVAPORATION RATES ESTUARY CIRCULATION VELOCITIES BOTTOM GEOLOGICAL FORMATIONS ICE TEMPERATURE IN DEPTH SUBLIMATION RATES LAND TEMPERATURE IN DEPTH EVAPORATION RATES TOPSOIL TRANSPORT MAGMA CONVECTION	PRECIPITATION RATE FLYING OBJECT LOCATION/IDENTIFICATION SEA SURFACE SALINITY CURRENT VELOCITIES COASTAL DEPTHS SHORELINE/SOAL MOVEMENTS TURBIDITY AND NUTRIENT AVAILABILITY SPECIAL WAVE LOCATION/IDENTIFICATION FISH/MAMMAL LOCATION/IDENTIFICATION ICE/SNOW THICKNESS/ROUGHNESS CRUSTAL SHIFTS/BULGES SOIL MOISTURE LAKE/RESERVOIR DEPTH GRAVITY FIELD

TABLE VIII. SUMMARY CAPABILITY STATUS PASSIVE MICROWAVE RADIOMETER

	FLYING, 1976	IN DEVELOPMENT	NEEDED
<u>FREQUENCY DEVELOPMENTS</u>			
RANGE EXTENSIONS	1.4-90 GHz	118-184 GHz 0.6 GHz	to 1000 GHz
FREQUENCY SCANNING	(FOR CHANNEL SELECTION OPTIMIZATION)		
NARROWER BANDWIDTHS	30 MHz	0.1 MHz	
<u>DETECTOR DEVELOPMENTS</u>			
HIGHER FREQUENCIES	100 GHz	300 GHz	1000 GHz
LOWER NOISE	SOLID STATE LOCAL OSCILLATORS SCHOTTKY BARRIER DIODES	PARA-AMPS MIXER COOLING TO 77°K	MASERS JOSEPHSON JUNCTIONS COOLING TO 7°K
<u>ANTENNA DEVELOPMENTS</u>			
SIZE INCREASES	1 m	4 m	100 m
SCAN IMPROVEMENTS	SMMR SCAN	SIMS TORUS	ELECTRICALLY SCANNED PHASED ARRAY

TABLE IX. SUMMARY CAPABILITY STATUS-ACTIVE MICROWAVE SENSORS

	DEMONSTRATED 1976	IN DEVELOPMENT	NEEDED
TRANSMITTER DEVELOPMENTS			
SHORT PULSE (NANOSECOND)			
ALTIMETERS	13.9 GHz (K_u) (S/C & A/C)	13.9, 35 GHz (K_u) (A/C ONLY)	1.2, 3.2, 9.5, 13.9, 35 GHz (L, S, X, K_u , K_d) (S/C & A/C)
POWER LEVELS (S/C)	2.5 kw PEAK (K_u)	---	1 TO 5 kw PEAK (ALL F)
PULSE LENGTH	1 ns (A/C) 12 ns (S/C)	1 ns (S/C)	1 ns (S/C)
LONG PULSE			
SCATTEROMETERS	9.4 GHz (X) (A/C ONLY) 13.9 GHz (S/C & A/C)	14.6 GHz (K_u) (S/C)	1.2, 9.5, 13.5 GHz (S/C & A/C)
POWER LEVELS (S/C)	40 w PEAK (K_u)	110 w PEAK (K_u)	50 TO 200 w PEAK (ALL F)
PULSE LENGTH	5 μ s (K_u)	5 ms (K_u)	BROAD RANGE (ALL F)
MEDIUM PULSE			
SYNTHETIC APERTURE IMAGING RADARS	0.67, 1.4, 9.6 GHz (A/C ONLY)	1.2, 9.6, 13.9 GHz (S/C & A/C)	1.2, 3.2, 5.3, 9.6, 13.7, 17.0, 35.0, 52.0 GHz (S/C & A/C)
REAL APERTURE IMAGING RADARS	9.2 GHz (A/C ONLY)	---	1.2, 3.2, 9.6, 35.0 GHz (A/C ONLY)
ATMOSPHERIC & PRESSURE SOUNDING RADAR	---	9.6, 13.9 GHz (A/C ONLY)	9.5, 13.9, 17.0, 35.0, 52.0 GHz (S/C & A/C)
SOLID STATE TRANSMITTERS	L-BAND (A/C ONLY)	L-BAND (S/C)	ALL FREQUENCIES AND POWER LEVELS
POWER LEVELS (S/C)	---	800 w PEAK (L)	1-20 kw PEAK (ALL F)
PULSE LENGTH	---	---	---
GENERAL - PULSE CHARACTER	SQUARE WAVE, ANALOG CHIRP FIXED PRF	DIGITAL CHIRP	DIGITAL CHIRP JITTERED PRF
COLLECTOR/EMITTER DEVELOPMENTS			
SPACECRAFT ANTENNAS			
ALTIMETERS	---	---	1 TO 12 m PARABOLAS OR ARRAYS (K_u TO L)
SIZE/TYPE/FREQUENCY	TO 1.5 m (K_u) PARABOLA	---	±10 DEG
CROSS TRACK BEAM STEERING	NADIR FIX	---	---
SCATTEROMETER	---	---	---
SIZE/TYPE/FREQUENCY	1.5 m PARABOLA	3 m STICK ARRAYS	3-30 STICK ARRAYS (K_u TO L)
SPECIAL IMPLEMENTATIONS	FIXED PATH	ORTHOGONAL FANS	CENTER FILL
ATMOSPHERIC RADAR	---	---	---
SIZE/TYPE/FREQUENCY	---	---	3 - 50 m STICK ARRAYS (X TO V_u)
SCANNING	---	---	HORIZON TO HORIZON
IMAGING RADAR	---	---	---
SIZE/TYPE/FREQUENCY	---	2 x 12 m PHASED ARRAY	PHASED ARRAYS TO 100m (L TO V_u)
SCANNING	---	---	STEP SCANNING TO EITHER SIDE
EARTH MOTION COMPENSATION	---	---	ANTENNA STEERING
SPECIAL IMPLEMENTATION	---	---	BISTATIC SAMPLING STACKED RECEIVER BEAMS SQUINTING MULTIPLE FREQUENCY IMPLEMENTATION
DETECTOR DEVELOPMENTS			
FREQUENCY RANGE, NOISE LEVELS	SEE TABLE PM-3, LIKE MICROWAVE RADIOMETERS		
RANGE FILTERING SENSITIVITY - CLOCK ACCURACY	10^{12}	---	10^{15}
DOPPLER FILTERING SENSITIVITY - ?	?	?	?
DATA PROCESSING SUPPORT			
ALTIMETER RANGE FEEDBACK	IN A/C	FOR S/C	FOR S/C
ATMOSPHERIC RADAR	SYNTHETIC APERTURE X BAND IN A/C USING OPTICAL CORRELATION	---	REAL TIME DIGITAL CORRELATION
SYNTHETIC APERTURE RADAR	REAL TIME DIGITAL & ANALOG CORRELATION FOR A/C (200 Mb/s, 20 MHz)	REAL TIME DIGITAL CORRELATION FOR (120 Mb/s) REAL TIME INFORMATION EXTRACTION FOR A/C	REAL TIME DIGITAL CORRELATION FOR S/C (2-6 Gb/s) REAL TIME INFORMATION EXTRACTION FOR S/C (WAVE SPECTRA, SHIP/ICEBERG LOCATION/ SIZING, VEGETATION COVER CATEGORIZATION, ETC.)

TABLE X. SUMMARY CAPABILITY STATUS FOR VISIBLE AND INFRARED RADIOMETERS

		FLYING, 1976	IN DEVELOPMENT	NEEDED
<u>WAVELENGTH DEVELOPMENTS</u>				
RANGE EXTENSIONS	- ATMOSPHERIC SOUNDERS AND COMPOSITIONAL MONITORS	30 μ m	47 μ m	To 1 mm
NUMBER OF CHANNELS PER INSTRUMENT	- ATMOSPHERIC SOUNDERS AND COMPOSITIONAL MONITORS	20	28	100
	- FEATURE IMAGERS	5	7	20
SPECTRAL RESOLVING POWER ($\lambda/\Delta\lambda$)	- ATMOSPHERIC SOUNDERS AND COMPOSITIONAL MONITORS	10 ⁶	10 ⁷ (DOPPLER LINEWIDTH LIMIT)	
	- SURFACE COLORIMETRY		20 nm	<10 nm
<u>COLLECTOR DEVELOPMENTS</u>				
SIMULTANEITY OF MEASUREMENT IN ALL CHANNELS	- ATMOSPHERIC SOUNDERS	5	28	?
OPTICS SIZES (d_o) INCREASE	- PLANETARY AND GEOSTATIONARY SOUNDERS AND COMPOSITIONAL MONITORS	0.4 m	0.5 m	2 m
FOCAL LENGTH (f) INCREASE		1 m	3 m	10 m
ANGULAR RESOLUTION $\approx d_o/f$	- FEATURE IMAGERS	10 ⁻⁴ deg	0.5 x 10 ⁻⁵ deg	10 ⁻⁵ deg
<u>DETECTOR DEVELOPMENTS</u>				
NUMBER OF DETECTORS PER CHANNEL	- FEATURE IMAGERS	1	20	1000
CRYOGENIC TEMPERATURE		77°K	5°K	?
LOWER NOISE LEVEL (NER), w/cm ² st		10 ⁻⁹ - 10 ⁻¹⁰	10 ⁻¹⁰ - 10 ⁻¹¹	10 ⁻¹² - 10 ⁻¹³
<u>SUPPORT SYSTEM DEVELOPMENTS</u>				
TELEMETRY SUPPORT	- FEATURE IMAGERS	15 Mb/s	200 Mb/s	2 - 6 Gb/s

TABLE XI. SUMMARY CAPABILITY STATUS LASER

	FLYING, 1976	IN DEVELOPMENT	NEEDED
WAVELENGTH DEVELOPMENTS			
RANGE EXTENSIONS	0.4 - 11 μ	0.3 - 11	10^{-3} mm - 10 mm
LINE PAIRS PER SENSOR	1	2	100
TRANSMITTER DEVELOPMENTS			
SHORT PULSE			
POWER	2-5 kw (AIRCRAFT)	2-5 kw (AIRCRAFT)	0.1-10 Mw (SPACECRAFT)
PULSE LENGTH	2-10	1-10	
CONTINUOUS WAVE			
POWER	0.1-3 kw (AIRCRAFT) BALLOON)	1-3 kw (AIRCRAFT)	0.2-10 kw (SPACECRAFT)
WAVELENGTH TUNING	(FOR ABSORPTION BAND WIDTH DETERMINATION)		
COLLECTOR DEVELOPMENTS			
APERTURE SIZE	5-30 cm	5-30 cm	50 cm
SCANNING	(FOR HORIZONTAL PROFILING)		
DETECTOR DEVELOPMENTS			
ABSORPTION COEFFICIENT DETECTABILITY	10^{-2} cm $^{-1}$	10^{-3} cm $^{-1}$	10^{-4} 10^{-5} cm $^{-1}$

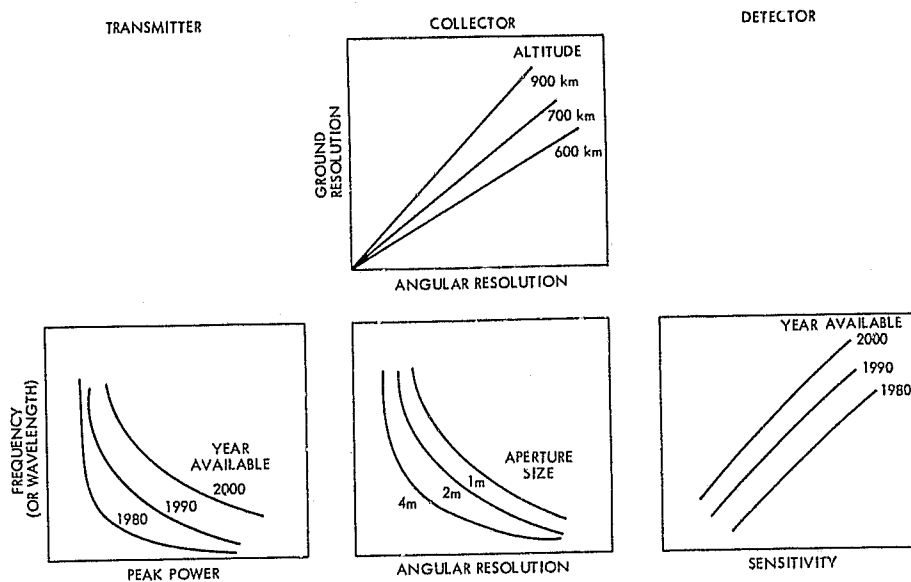


FIGURE 1. GENERALIZED SENSOR DESIGN

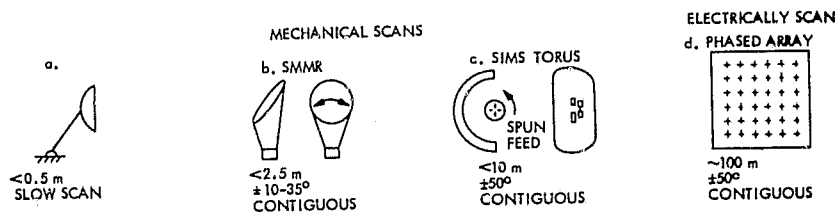
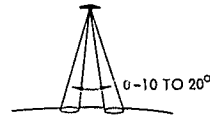


FIGURE 2. PASSIVE MICROWAVE ANTENNA SCANNING TRENDS

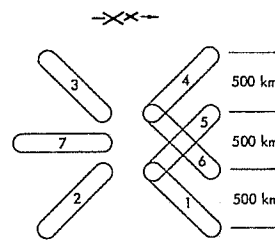
ORIGINAL PAGE IS
OF POOR QUALITY

- a. NARROW NADIR BEAM OR CROSSTRACK SCANNING



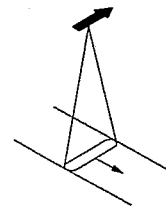
ALTIMETRY
BATHYMETRY
WAVE HEIGHT SPECTRA
ICE/SNOW THICKNESS/
ROUGHNESS

- b. MULTIPLE FAN BEAMS
1-4: $\pm 45^\circ$ CROSSTRACK
5-6: ORTHOGONAL CENTERFILL
7: MULTIPLE INCIDENCE CALIBRATION



WIND SPEED AND DIRECTION

- c. SCANNING FAN BEAM SPINNING SPACECRAFT OR ANTENNA MONO OR BISTATIC REAL OR SYNTHETIC APERTURE

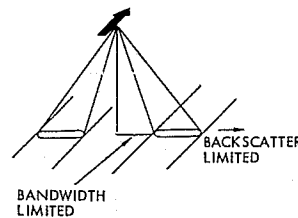


PRESSURE/DENSITY PROFILE
CLOUD HEIGHT/EXTENT
PRECIPITATION POTENTIAL,
ACTUAL AND VELOCITIES
HUMIDITY COLUMN
PARTICLE OR CLOUD
VELOCITIES

EITHER IMPLEMENTATION

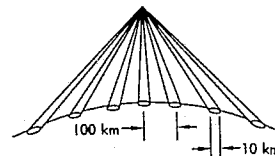
SNOW EXTENT
SOIL MOISTURE
SOIL TYPE
SURFACE ROUGHNESS
VEGETATION COVER, TYPE,
GROWTH AND STRESS

- d. FIXED IMAGING FAN BEAMS BOTH SIDES CROSSTRACK OR WITH FORWARD/BACKWARD SQUINT REAL OR SYNTHETIC APERTURE



HIGH RESOLUTION IMAGES
WAVE SPECTRA
SHIP, ICEBERG, CREVASSE
LOCATION/SIZING

- e. BISTATIC WITH THINNED ARRAY SEPARATE SEND AND RECEIVE ANTENNAS EACH BEAM CAN BE TREATED AS A SYNTHETIC APERTURE



ALTIMETRY
BATHYMETRY
WAVE SPECTRA SAMPLING
WIND SAMPLING

FIGURE 3. SAMPLE ILLUMINATION POSSIBILITIES

C-2

N78-14406

TECHNOLOGY ADVANCES IN ACTIVE AND PASSIVE

MICROWAVE SENSING THROUGH 1985

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ABSTRACT

As a result of a growing awareness by the remote sensing community of the unique capabilities of passive and active microwave sensors, these instruments are expected to grow in the next decade in numbers, versatility and complexity. The Nimbus-G and Seasat-A Scanning Multichannel Microwave Spectrometer (SMMR), the Seasat-A radar altimeter, scatterometer and synthetic aperture radar represent the first systematic attempt at exploring a wide variety of applications utilizing microwave sensing techniques and are indicators of the directions in which the pertinent technology is likely to evolve. The trend is toward high resolution multi-frequency imagers spanning wide frequency ranges and wide swaths requiring sophisticated receivers, real-time data processors and most importantly, complex antennas.

1. INTRODUCTION

The launch in 1978 of the Nimbus-G and Seasat-A satellites will mark the beginning of a new phase in the development of active and passive microwave sensing of the earth. Nimbus-G will have as part of its payload the Scanning Multichannel Microwave Radiometer (SMMR), which is a passive microwave imager operating at five frequencies between 6.6 and 37 GHz; Seasat-A, in addition to a duplicate of the SMMR, will have on board an L-Band Synthetic Aperture Radar (SAR), a Ku-band scatterometer, and a Ku-band altimeter. These instruments reflect a new understanding by the remote sensing community of the broad potential of microwave sensors and a realization of the need to overcome the shortcomings of the visible and infrared type instruments which have until now dominated the remote sensing field. Despite the fact that a number of microwave sensors have been flown in space previously, particularly on Nimbus 5 and 6 and Skylab, and which have conclusively demonstrated the meteorology applications of millimeter radiometers, the Nimbus-G and Seasat-A instruments represent the first major systematic effort to explore a wider variety of applications. Recent technology advances in solid state power sources, low noise receiver componentry, low-loss ferrite devices, and others, have substantially facilitated this step. This paper will explore some of the additional advances required to allow further efficient exploration of microwave remote sensor applications and to pave their way for operational use.

2. PASSIVE MICROWAVE TECHNOLOGY

Microwave radiometers can basically be divided into two types: spectral and continuum. "Spectral" radiometers have very narrow bandwidths tuned to or near mi-

microwave resonance lines such as oxygen and water vapor, and by their nature are used to sense atmospheric parameters. The advantages of this type of sensing have been recognized early and led to the development of the Nimbus E Microwave Spectrometer (NEMS) and the Scanning Microwave Spectrometer (SCAMS) on Nimbus 5 and 6 respectively. The spectacular success of these sensors has led to the implementation of an operational temperature sounder, the Microwave Sounding Unit (MSU) for the Tiros-N series of meteorological satellites. It also has generated a strong desire to sense at higher (mesospheric) altitudes and to study molecules such as ClO with higher frequency resonances. These desires translate into high frequency (>100 GHz), narrow band (<100 MHz) systems which in turn drive the need for near-term subsystem technology advances in areas such as quasi-optical devices, submillimeter stable oscillators and harmonic generators, and most importantly, low-noise mixers of various types. The need to improve the areal resolution of these sensors and to operate from geosynchronous orbits for improved local coverage also indicates higher frequency operations, as well as higher angular resolution at a given frequency. The subsystem technology requirements stemming from these are the same as above with the additional need for large aperture, high precision antennas. Ten meter diameter parabolic antennas capable of operation up to 300 GHz are typical.

"Continuum" radiometers are used for sensing targets with very broad spectral features covering octaves in frequency. Systems of this type have been flown on Skylab, Nimbus 5, and Nimbus 6 for studies of the signatures of a number of primarily terrestrial surface phenomena. These experiments as well as a broad ground and aircraft research effort have led to the conclusion that multi-frequency, multi-look-angle systems are needed to sense complex phenomena such as soil moisture. The SMMR is the first spaceborne sensor of this type and clearly points to the need for technology development in advanced large aperture antennas capable of operation over a broad set of frequencies (to conserve size and weight) and for some applications, of performing observations at a number of look angles. Compounding the complexity of both continuum and spectral radiometers is the fact that practically all applications call for wide area or, in the case of the atmosphere, for large volume sensing. This implies imaging systems and therefore the antennas have to have scanning capability as well.

Table I summarizes the passive microwave related subsystem technology development needs. They are driven by the system requirements which in turn are derived from the user and applications requirements. The trend towards extended sensing capability clearly requires the development of multifrequency imagers spanning wide frequency ranges which critically depend on sophisticated front ends and complex antennas. A good example of a design attempting to meet most of these requirements is the Shuttle Imaging Microwave System (SIMS) proposed by the Jet Propulsion Laboratory. The system consists of an antenna reflector which is a section of a parabolic torus and is illuminated by a number of rotating feeds disposed like the spokes of a wheel. Each feed can operate at a different frequency limited only by the reflector surface tolerance. The rotation of the feeds provides either transverse or conical scanning depending on the geometry used. The antenna being over 4 m. in diameter, there is ample room for the radiometers on the rotating element. Power is provided by a non-contacting rotary transformer and the data output is via short-range RF link.

3. ACTIVE MICROWAVE TECHNOLOGY

Active microwave sensors of the earth's surface fall into three main classes: altimeters, scatterometers and imaging radars. A number of sophisticated altimeters and one scatterometer have been flown on several space missions to date, and one of each type of sensor is being developed for Seasat-A. These instruments exhibit a high level of maturity and no requirements for significant technical developments are anticipated in the near future. The situation with imaging radars is quite different. The first known imaging radar in space will be the Seasat-A SAR and its technical shortcomings are already evident. This fact coupled with the

rapidly increasing sophistication of a broad class of imaging radar data users already shows requirement trends towards sensing increasingly complex phenomena, frequent revisits of given areas, stereo imaging, and improved quality imagery. A number of systems-level requirements can be derived from these needs: multiple frequency operation, multiple look angle imagery, wide swath widths, possibly fore and aft squint to obtain stereo in a single pass, and fine resolution capability with high signal-to-noise, low speckle pixels. At the subsystem level, two main elements are driven by these requirements and will need substantial technology advances in the near future. One is antennas: not only are they large, but they need to operate at multiple frequencies and develop beams looking in a number of directions either simultaneously or in very rapid sequence. Phased arrays, possibly of the dispersive type might offer solutions but they typically are highly expensive and only operate in one band, thereby presenting cost, area, volume and weight problems. Innovative mechanically scanned antennas might present attractive solutions despite the undesirability of such systems in space. The other subsystem area needing major effort is the SAR data preprocessor or correlator. This subsystem is required to perform complex and very high rate computations in real time and on board the spacecraft to reduce the output data rates to manageable levels. NASA's Office of Aeronautics and Space Technology recognizing this need has taken initiative to sponsor the development of the required technology, removing this as an obstacle to the design of advanced SARs.

Table II summarizes the synthetic aperture radar system and derived subsystem technology requirements. The antenna requirements in particular represent interesting technological challenge and meeting them is the key to the utilization of SARs for a wide variety of remote sensing applications.

4. CONCLUSION

Although the only predictable thing about the future is its unpredictability, active and passive microwave sensing is rapidly coming of age and, provided a number of technological challenges are met, particularly in the antenna area, it is felt that by 1985 every major new remote sensing complex will include one or several microwave sensors.

5. ACKNOWLEDGEMENT

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6. REFERENCES

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2. "A forecast of space technology 1980-2000", NASA publication SP-387, January 1976.

TABLE I TRENDS IN PASSIVE MICROWAVE SENSING

USER/APPLICATIONS REQUIREMENTS	SYSTEM REQUIREMENTS	SUBSYSTEM TECHNOLOGY REQUIREMENTS
- HIGH ALTITUDE ATMOSPHERIC PHENOMENA - HIGH FREQUENCY SPECTRAL LINES	- HIGH FREQUENCY - NARROW SPECTRAL LINES	- QUASI-OPTICAL DEVICES - HARMONIC GENERATORS - PHASE LOCKED LOCAL OSCILLATORS - LOW NOISE MIXERS
- HIGH SPATIAL RESOLUTION - GEOSYNCHRONOUS OPERATION	- HIGH ANGULAR RESOLUTION - HIGH FREQUENCY	- AS ABOVE - LARGE ANTENNA APERTURES - PRECISION ANTENNAS
- 2D/3D SENSING	- IMAGING	- AS ABOVE - SCANNING ANTENNAS
- COMPLEX PHENOMENA SENSING	- MULTIFREQUENCY SYSTEMS - MULTIPLE LOOK ANGLE SYSTEMS	- AS ABOVE - BROADBAND FEEDS - SHARED APERTURE ANTENNAS - VARIABLE LOOK ANGLE ANTENNAS
↓ EXTENDED REMOTE SENSING CAPABILITY	↓ MULTIFREQUENCY IMAGERS SPANNING WIDE FREQUENCY RANGE	↓ SOPHISTICATED FRONT ENDS AND COMPLEX ANTENNAS

TABLE II TRENDS IN ACTIVE MICROWAVE (SAR) SENSING

USER/APPLICATIONS REQUIREMENTS	SYSTEM REQUIREMENTS	SUBSYSTEM TECHNOLOGY REQUIREMENTS
- COMPLEX PHENOMENA SENSING	- MULTIFREQUENCY SYSTEMS - MULTIPLE LOOK ANGLE SYSTEMS	- PRECISION LARGE APERTURE ANTENNAS - SCANNING ANTENNAS
- FREQUENT REVISIT	- WIDE SWATH COVERAGE	- AS ABOVE
- STEREO IMAGERY	- FORE AND AFT SQUINT	- AS ABOVE
- HIGH QUALITY IMAGERY	- FINE RESOLUTION - MULTIPLE LOOKS - HIGH SNR	- AS ABOVE - EFFICIENT TRANSMITTERS - ON-BOARD DATA CORRELATORS - IMAGE DATA COMPRESSORS
↓ EXTENDED REMOTE SENSING CAPABILITY	↓ MULTIFREQUENCY, WIDE SWATH, MULTILOOKANGLE, HIGH RESOLUTION SARs	↓ COMPLEX ANTENNAS AND ON-BOARD, REAL-TIME DATA PROCESSORS

THE UTILITY OF SHORT WAVELENGTH (<1MM) REMOTE SENSING TECHNIQUES
FOR THE MONITORING AND ASSESSMENT OF HYDROLOGIC PARAMETERS

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ABSTRACT

Considerable effort accompanied by significant progress has occurred in the last several years in applying visible and infrared remote sensing measurement to water resources management needs. The requirements of the water resources management and hydrologic communities have been recently compiled by the World Meteorological Organization. Remote sensing programs that respond to these requirements have employed a study and development approach involving information content and modelling research utilizing a properly phased mix of remote sensing platforms and approaches involving ground-based research and observations from aircraft and spacecraft. The Landsat and NOAA environmental satellite systems have provided spacecraft observations in recent years that are proving to have utility in several hydrologic areas. The major areas where the needs of water resources management are being met involve the mapping and monitoring of snowcovered areas, hydrologic landuse, and surface water area. In the case of snowcovered area mapping the transfer of technology process is now being accomplished in the Western United States in a cooperative effort involving 6 federal agencies and 3 state agencies along with NASA. A new collaborative effort of the U.S. Army Corps of Engineers and NASA involves the mapping of landuse by Landsat and its use in hydrologic engineering watershed models employed in flood control/waterworks planning, design, and management. Improved systems planned for implementation in the 1978-1981 time frame can be expected to result in increased utilization of visible and near infrared remote sensing observations. Research being carried out now also suggests that microwave observations may be able to monitor more fundamental hydrologic variables and, thereby, make a more essential contribution to water resources management.

1. INTRODUCTION

Considerable progress has been made in the past few years in applying remote sensing to hydrological/water resources management problems. Reviews of progress have been provided at various points in time to document this progress (Rango, et al., 1974; Otterman, et al., 1976). The development of remote sensing in this general area has had a strong applied flavor to it as opposed to a scientific hydrology emphasis. This is because of the heavy involvement of the National Aeronautics and Space Administration (NASA) in supporting remote sensing research and the emphasis on applications where water resources is included in the NASA Earth Observations Program. In addition, largely because of the NASA support and involvement in earth-oriented remote-sensing research, the emphasis has been skewed toward use of spacecraft data. The launch in 1972 of the Landsat spacecraft with its Multispectral Scanner Subsystem (MSS) and the flight of the Very High Resolution Radiometer on the NOAA-2 spacecraft operated by NOAA has furthered this emphasis due to the high resolution, repetitive coverage those observational systems provided. The intent of this paper is to cover the advances that

have been made in applying remote-sensing to hydrology and, in doing so, not discount the utility of remote sensing from ground-based and aircraft platforms. However, because of the need to be able to better inventory and manage water resources over larger and larger areas due to increased population, accompanying needs, and the inherent advantage of spacecraft observations for repetitively monitoring very large areas, much of the discussion in the paper will be on the application of spacecraft systems.

2. OVERVIEW OF A REMOTE SENSING APPLICATIONS PROGRAM FOR WATER RESOURCES MANAGEMENT

It is helpful to keep in mind a general evolution structure as one develops a remote sensing program that is attempting to meet the needs of the water resources management community. Such a structure is described in Figure 1a with additional ideas schematically depicted in Figures 1b and 1c.

Figure 1a particularly tries to point out that one cannot develop an effective remote sensing program without considerable knowledge of how water resources management is accomplished and what methodology or tools are employed. Once having established a program then one can proceed to use all data, technology and analysis methods possible. This idea is conveyed by the right hand "loop" of Figure 1a. As one becomes involved in activities characterized by this concept development loop, one must keep in mind that such a program must eventually get to a point where quasi-operational tests or Applications Systems Verification and Transfer (ASVT) projects become appropriate. These projects will, if appropriately conceived and implemented, provide user agencies (federal, state, etc.) with a definitive measure of improvement in information reliability, accuracy, and timeliness and cost savings realized using remote sensing versus conventional methods or tools. From an ASVT should come enough information for a user to make a decision as to whether to invest both manpower and dollars in implementing remote sensing approaches as additional or ancillary information gathering tools or whether to replace conventional methodology with remote-sensing-based approaches.

Figure 1b is provided to indicate that both information content research and models should be used in a water resources remote sensing program. Models are emphasized, in particular, because there are different types and they perform necessary and important functions. One general type of model is the radiative transfer model that must be used to test whether there is a possibility of extracting useful information (soil moisture, snow water content, surface temperature, etc.) from remote sensing measurements and to offer a sound physical basis and explanation for the use of remote sensing to gather information. The other type of model is a physical model or systems model (e.g. of a watershed/runoff system or a reservoir management system). These models help if used for sensitivity studies that offer insight to the most important variables affecting output variables (e.g. runoff) or as a means of quantitatively describing the utility of remote sensing without the expense and effort involved in going through a complete observational or water resources management exercise (Salomonson, et al., 1975; Sohn et al., 1976). Models are particularly important in water resources management because they very commonly are employed as a management decision-making mechanism.

Figure 1c is provided to make the point that a proper mix of various types of remote sensing studies and observing platforms should be used as a remote sensing approach goes from being an idea to operational implementation. The progression from theory to laboratory, ground-based platforms (e.g., "cherry-picker"-mounted instrumentation), aircraft etc., is particularly necessary to conserve resources and provide proper validation for proposals to fly instrumentation on spacecraft where required resources or investment are quite large.

There is quite a substantial and useful array of observing platforms that have and are producing data of utility for water resources management, or have and are producing data which has great potential in research projects. Existing platforms and brief descriptors of the data they produce are given in Table 1. From this point on, the purpose of this paper is to describe the progress that has been made in developing the application of visible and infrared data gathered from platforms listed in Table 1. This paper will generally follow a pattern described by the schematics given in Figure 1a. Progress in information content and modelling research will be described followed by brief descriptions of on-going ASVT projects that are involving User Agencies and NASA in cooperative efforts. Near the conclusion of the paper a brief look to the future will be taken to offer insight as to the progress that might be expected in the 1980's.

3. WATER RESOURCES REQUIREMENTS AND INFORMATION CONTENT RESEARCH

As already noted, in order to determine the true effectiveness of remote sensing for water resources management operational needs and measurement requirements must be defined and

the corresponding capabilities of remote sensing evaluated. Such an attempt has been made by the World Meteorological Organization (WMO, 1976) with particular reference to satellite data for planning purposes. The observational satellite requirements established in the WMO document will be used to evaluate the hydrologic contributions of present and future visible and infrared remote sensing capabilities. As pointed out by the WMO (1976), resolution requirements must be tailored to the size of the drainage basin because of varying operational and experimental applications. Basin size ranges were thus established: "A" - less than 100 km²; "B" - between 100 and 1,000 km²; and "C" - greater than 1,000 km². Another complicating factor in formulating requirements is that they will certainly vary from one country to another because of different levels of research and operational activities. Combined with the resolution requirement, accuracy and frequency of measurements were also estimated.

Because of their value and general non-availability, the hydrologic remote sensing requirements set by the Informal Planning Committee (WMO, 1976) are presented in Table 2. It must be recognized that these requirements are preliminary and under review by WMO, and that the WMO is in no way responsible for the numbers or the form of their presentation here. The information in Table 2, however, provides basic data for evaluation of the informational content of current and proposed remote sensors. In this discussion of informational content, the visible and infrared capabilities will be examined in detail, whereas potentials for microwave sensing or satellite data relay will only be identified. The information presented by Ulaby (1977) should be useful for completing a microwave evaluation in reference to Table 2.

In order to provide a measure of snowcover, the snowline position is often delineated. The snowline spatial resolution requirements for watershed sizes "B" and "C" in Table 2 can currently be obtained with the Landsat Multispectral Scanner Subsystem (MSS) (0.6-0.7 μ m band) and the NOAA Very High Resolution Radiometer (VHRR) or the NOAA Synchronous Meteorological Satellite (SMS); however, Landsat systems only provide coverage twice every 18 days with two satellites. The resolution and stringent frequency requirements may be alleviated, however, if NOAA and Landsat are used in tandem with their respective frequency and resolution characteristics supplementing one another. In the future Landsat-D will meet the 30 m snowline resolution requirement for watershed size "A".

The NOAA-VHRR meets the total snowcover spatial resolution requirements for "B" and "C" watersheds, and Landsat satisfies the "A" watershed requirements. Accuracies of $\pm 5\%$ of snowcovered area are possible from Landsat and NOAA observing systems. The required frequency can only be currently acquired from NOAA or SMS systems. Once more the judicious combination of NOAA and Landsat should improve their individual applicability for snowcover mapping. At the present time there is no known method for remotely sensing snow water equivalent from space. Comparison of visible and near infrared band reflectance provides only qualitative delineation of snow areas possessing free water at the surface as a result of melting. It is possible that the development of microwave sensing will allow significant contributions in the areas of water equivalent and free water content determination over large regions. At given locations the satellite data collection system could be used profitably with automated snow instruments.

The determination of snow, temperature and albedo are amenable to satellite capabilities and resolutions for "C" watersheds are possible. The thermal infrared sensor on the NOAA-VHRR can apparently provide observations accurate to about $\pm 2^\circ\text{C}$ if appropriate accounting for atmospheric effects is used. In 1978, the HCMM will be capable of making surface temperature measurements with 500 m resolution. Landsat-C will have a thermal infrared resolution of about 240 m and in 1981 Landsat-D will reduce the thermal infrared resolution to 120 m. At that time resolution requirements for all size watersheds will nearly be met, but none of the satellites will be capable of 6-hour frequency of coverage except, possibly, for the TIROS-N systems (see Table 3). Much remains to be done to show that the thermal infrared measurements obtainable from satellites can be effectively used in snow studies and monitoring.

Satellites also provide measurements of bi-directional reflectance in the visible and near infrared. However, not much is really known as to how well these measurements can be related to the albedo and energy balance over snow surfaces. The comparison of outbound radiation to inbound radiation in existing sensor wavelength regions may permit an albedo estimate, but not every 6 hours as required.

Overall, there has been considerable progress and there appears to be a significant remaining potential for using satellite data to estimate snow information with visible and infrared systems. The most common problem seems to be the meeting of stringent frequency of coverage requirements. A review of the various remote sensing techniques and potentials for snow mapping is given by Rango and Itten (1976).

Measurement of various hydrological elements of lake and river ice (indicated in Table 2) by visible and infrared means has many similarities to the measurement of snow on land. Both ice line and continuous ice cover area can be measured with the remote methods. Ice line resolution of 30 m must wait until Landsat-D in 1981 (Landsat-C will have a single band resolution of 40 m (on the Return Beam Vidicon (RBV) systems) that may be useful, however). Otherwise resolution and accuracy requirements can be met, but frequency of coverage remains a major problem. Ice concentration and movement applications are hindered by both the resolution and frequency of coverage limitations. "C"-size elements can be measured now with Landsat-2 resolution, however, "A" and "B" areas must await the resolution on Landsat-D. Daily coverage is not possible now or in the near future. Ice type can now be measured every-day for "C"-size elements with NOAA-VHRR and twice every 18 days with Landsat on "B"-elements, clouds permitting. Landsat-D (and possibly Landsat-C) will permit measurements on the "A"-elements. Only NOAA-VHRR can meet the frequency of coverage requirements for ice type delineation. There is no known visible or infrared technique for measuring ice thickness and no other useable technique from space in the immediate future. Short-pulse radars have, however, been used on aircraft over the Great Lakes for thickness measurements (Vickers, Heighway, and Gedney, 1974). Ice surface temperature can be obtained daily with 1,000 m resolution with NOAA-VHRR now, but no immediate capability for 30 or 100 m resolution is foreseen (Landsat-D will come the closest with 120 m thermal infrared resolution).

As already indicated, a common theme running through snow on land and lake and river ice observational requirements with reference to remote sensing is the inadequacy of observational frequency. This will also be true of several of the remaining hydrological elements. To resolve this problem several suggestions are made. First, these frequency requirements may be too stringent and as a result, they each should be reconsidered. For example, the discussion of models will show that frequency of snow area coverage for snowmelt models need not be anywhere near as repetitive as daily, even when daily snowmelt runoff is being forecast. Second, satellites should not be considered for use separately when conventional data are available concurrently. Whenever snow and ice applications are considered, NOAA and Landsat should be used as a cooperative "system," rather than in competition with each other. Such a "system" would have the advantages of high observational frequency and high spatial resolution which should increase the applicability of the remote data across a wide range of watersheds. Third, if the daily and hourly frequency requirements prove to be real and are the major drawbacks to the use of the data, efforts should be made to ascertain if a geosynchronous Landsat-type capability should be implemented. Such a satellite capability would allow daily observations, clouds permitting, and in critical situations data could be collected every five minutes, if necessary.

Studies of glaciers, as shown in Table 2, do not require the same high frequency observations as a result of their relative stability when compared to the fluctuating seasonal snow and ice cover. Inventories of glaciers every 10 years can be accomplished now using Landsat for "B"- and "C"-size glaciers, and "A"-size glaciers should be measurable by Landsat-D in 1981 and perhaps even by Landsat-C in 1977. Snowcovered area and mass balance computations can be carried out with the currently existing Landsat system. Monitoring of glacier surges can be done with Landsat now for "B" and "C" glaciers and should be extended to "A" glaciers with the Landsat follow-on missions. Length variation on "A"-size glaciers will be most effectively measured by specially planned aircraft flights. In general visible and infrared satellite capabilities are well suited to the needs of glacier monitoring (Gloersen and Salomonson, 1975).

Surface water monitoring presents a two-fold problem for remote measurement. Frequency of coverage is again limiting with requirements ranging on Table 2 from every 10 minutes to every 4 days. This problem is compounded by needed resolutions of 10-100 m. As a result, neither NOAA nor Landsat is generally applicable. For "C"-size watersheds Landsat can make useful measurements if it passes over during a cloud free period. Landsat-D will improve the resolution capability down to "B"-size basins, but not the frequency of coverage. The fact that clouds very often are present during flooding events indicates that this may be a situation where an all-weather, synthetic aperture radar (SAR) capability is required. Data taken over land with the synthetic aperture radar (25 m resolution) on Seasat-A will be very interesting to analyze in regard to areal extent of surface water, saturated soil areas, and flood extent. Lake or river stage will be most effectively measured using satellite data collection systems that allow measurements every 10 minutes, although the data may only have to be relayed to the satellite once every 1-3 hours. The last remaining hydrological element, floodplain boundaries, needs to be surveyed only infrequently, but with a resolution (10 m) too stringent for near-future space applications. It has been shown that remote sensing, however, has important roles to play in various phases of floodplain management (Sollers, Rango, and Henninger, 1977). It may prove most beneficial to use a multispectral scanner on a high altitude (20 km) aircraft to produce the desired resolution and spectral discrimination. Many floodplain applications, however, may be amenable to resolution on Landsat-D.

Soil properties are a difficult area for visible and infrared remote sensing because most properties of hydrologic interest are subsurface features and the remote measurements are indicative only of the surface. Soil associations have been mapped adequately in South Dakota (Westin and Frazee, 1975) using Landsat and soil survey mapping has been improved using multispectral aircraft data in Pennsylvania (Mathews, et al., 1973). However, only surface features are delineated and not the hydrologic characteristics with depth. The moisture content profile is not obtainable with visible and infrared measurements, although the use of thermal infrared aircraft data has been shown to have a high potential for bare soil, surface layer soil moisture sensing (Schmugge, et al., 1977). The diurnal surface temperature variation is well correlated with conventional ground measurement of soil moisture in the 0-2 cm layer. Even when the soil surface is covered by vegetation, canopy surface temperature when compared to air temperature provides a means for inferring crop status and associated soil moisture conditions (Idso et al., 1975). Diurnal surface temperature data from the HCMM to be launched in 1978 with 500 m resolution will be used to test these initial aircraft results. The use of microwave sensing for soil moisture measurements to even greater depths has significant potential as indicated by Ulaby (1977) at this symposium. Other types of moisture profile measurements and water balance models will have to be combined with the remote sensing data to extend sampling down to 100 cm. Where the remote data is applicable (near the surface) estimates should fall within the required accuracy of $\pm 10\%$ of field capacity. Visible and infrared data can do very little for soil temperature profiles, infiltration/percolation, depth of seasonal frost, and detection of permafrost. Once again the pertinence of microwave sensing should be explored.

Groundwater level or aquifer extent cannot be obtained directly from visible and infrared data; the data collection system will have to be used to relay groundwater level recorder data. The mapping of surficial aquifers, however, can be inferred by other features such as vegetation, soils, and river channels. Ozoray (1975) used Landsat data to find areas of sand and gravel accumulations along streams in Alberta, Canada that produced significant water yield when drilled. Associated with this application is the mapping of geologic lineaments or fractures with Landsat in many areas of the United States. Groundwater wells generally tend to produce higher yields when drilled at the intersections of these fractures. Such information from Landsat and Skylab have been used to improve the siting of new wells (Goetz et al., 1975; Johnson Space Center, 1974). The location of discharge into rivers and lakes can be inferred with thermal infrared data by the delineation of temperature anomalies in the water bodies. Landsat-D resolution should provide useful data for lakes, but high resolution aircraft data will be required for locating discharges in rivers. The location of springs will also require airborne thermal sensing.

Drainage basin parameters are extremely important for watershed characterization and as inputs to watershed models. The only drainage basin element listed in Table 2 not available from space now or in the foreseeable future is surface slope (unless spaceborne radar altimetry is more successful than anticipated). Such measurements will have to be made with low flying aircraft or on the ground. On the other hand, existing satellites can meet the resolution, accuracy, and frequency requirements for all "C"-size basins for all the other parameters. Landsat-D resolution will allow "A" and "B" watersheds to also be mapped adequately. An example of Landsat physiographic mapping is given by Rango, Foster, and Salomonson (1975). Results in land cover analysis with Landsat have been most impressive and will be covered in detail by Ragan (1977) at this symposium.

Precipitation measurement over land using remote sensing is extremely difficult. Visible and infrared data have been used to track cloud systems and correlate pattern and cloud top temperature generally to ranges of possible precipitation totals (Davis, 1974). It would appear, however, that the satellite data collection and relay system would be an effective way for improving the estimation of precipitation in the future. These same statements are generally true of evapotranspiration as well, although various factors affecting evapotranspiration, such as temperature, albedo, and crop and moisture stress, can be measured or delineated. These associated factors could be used in existing or new methods for calculation of evapotranspiration and result in an improvement over current techniques.

In water quality, information on turbidity, suspended sediment, color, algae blooms, and surface film detection can be obtained for "B" and "C" water bodies now and from "A" water bodies in the future using Landsat-D. In addition spectral discrimination improvements on Landsat-D should increase the information content associated with the above hydrological elements. The frequency of coverage is again the major limiting factor. Temperature profiles will not be possible with remote sensing but data relay techniques will be suitable. Surface temperature measurements for "B" and "C" water bodies will be feasible only for below 0°C and above 4°C . The accuracy requirements in the $0-4^{\circ}\text{C}$ interval are too detailed for remote

sensing methods. The frequency of observations required would have to be handled by synchronous satellites or data relay techniques.

4. MODELLING APPLICATIONS

Visible and infrared remote sensing data have been found to be extremely useful in various types of watershed modelling as described by Ragan (1977). Advantages to the data include its timeliness, wide area coverage, adaptability for computer processing, and its generally being less expensive to use. The use of remote sensing data in watershed models is probably the most efficient way to exploit this new information. To provide an example of how the remote measurements could be used in modelling, a very specific subset of hydrologic remote sensing data will be discussed, namely, the use of snowcovered area. Other types of model applications, such as planning, partial area, and river basin models, will be discussed by Ragan (1977).

The least complex and conventional way to use remotely-sensed snowcover data is to use it as an independent variable in a regression model to predict seasonal runoff. Rango, Salomonson, and Foster (1977) used low resolution (4km) ESSA 9 data and simple photointerpretation techniques to map snowcovered area during early April over the Indus and Kabul River basins in the Himalayas. The early spring snowcovered area was significantly related to April 1 through July 31 streamflow in regression analyses for each watershed (Indus River, 1969-1973, $r^2 = 0.82$, and Kabul River, 1967-1973, $r^2 = 0.89$). Predictions of 1974 seasonal streamflow using the regression equations were within 7% of the actual 1974 flow. Because of inadequate hydrometeorological data, conventionally based streamflow predictions are not possible in some of these remote regions, and the satellite-derived runoff estimates have immediate applicability for improved water resources management.

For Landsat such a long period of snowcovered area data are not available and other approaches must be tried. Thompson (1975) in Wyoming found that the snowcovered area on a particular date was better related to the accumulated runoff/total seasonal runoff ratio than to just the seasonal runoff in a simple regression relationship. As a result if accumulated runoff was known (which is usually the case), then snowcovered area could be used to estimate total seasonal runoff with a small data base. Such relationships are not only useful for total flow forecasts but also for short term forecasts of time distribution of seasonal runoff. Additional studies (A. Rango, unpublished data, 1977) show that when snowcovered area data is combined with conventional hydrometeorological data in multiple regression approaches, errors associated with the updating of seasonal streamflow forecasts can be reduced on certain watersheds.

The alternative to regression models is the input of snowcovered area to numerical hydrologic models for daily and longer term streamflow predictions. In the Northwest United States snowcovered area can be inserted into the Streamflow Synthesis and Reservoir Regulation (SSARR) model (U.S. Army Engineer Division, 1975). The model requires snowcovered area data infrequently throughout the season to more accurately deplete the water equivalent of the snowpack and to distinguish the watershed areas actively producing snowmelt or experiencing a rain on snow situation. To further improve simulations a snow area-elevation zone input option is available in the SSARR model.

A more simple model has been proposed by Martinec (1975) in which basin snow water equivalent is not a necessary model parameter. The only data necessary in order to predict daily runoff are watershed runoff and recession coefficients, a degree day factor, temperature, and snowcovered area in various elevation zones. For each zone the degree day factor, extrapolated temperature, and snow extent are used to calculate melt according to existing conditions. The runoff and recession coefficients are used to calculate the amount of water reaching the stream on a given day. Streamflow forecasting with the method is limited only by the adequacy of the temperature predictions for the period of forecast. Martinec estimates (personal communication, 1976) that four satellite snowcovered area observation dates during the snowmelt season are sufficient to construct a snow-area depletion curve for keeping track of changing snowcover as a result of melting.

None of these snowmelt modelling examples requires daily snowcovered area measurements as was indicated necessary by WMO (1976). It appears that satellite snowcovered area data available only twice every 18 days would still have direct pertinence for several hydrologic applications, especially those employing watershed models.

5. QUASI-OPERATIONAL DEMONSTRATION TEST PROJECTS

The various remote sensing research efforts in hydrology have produced positive results in certain areas of water resources that have led to the establishment of quasi-operational tests of the remote sensing technology. These results and subsequent tests are in two primary areas: snowcover mapping and snowmelt runoff prediction; and hydrologic land use analysis.

The first test is the Operational Applications of Satellite Snowcover Observations Project, a NASA Applications Systems Verification and Transfer (ASVT) project that was discussed in detail at the Tenth International Symposium by Rango (1975). The Snow ASVT objectives, organization, and study areas remain the same as outlined in 1975. The major change has been the planned switch of emphasis from transferring the snow mapping technology to determining how the satellite snow data can be used in runoff predictions. In coordination with this, the real time data delivery goal of 72 hours is nearly being accomplished. NOAA-VHRR and -VISSR data is received by the study centers in 1-3 days after acquisition and Landsat quick look data arrives in 2-7 days after acquisition. The cost/benefit study is underway and is scheduled for completion near the end of the project, about December 1978. In the cost/benefit study early effort is being made to stratify the entire population of watersheds in the Western United States on the basis of importance of snow for producing runoff, single or multiple reservoir water use and reservoir characteristics, and similarity to ASVT study watersheds. As a result the fundamentals of reservoir operation for various water uses are being defined and related to snow mapping capabilities. As the cost/benefit study progresses, emphasis will turn to evaluating results from each ASVT study area in the framework of potential benefits to the entire population of Western United States watersheds. Remaining tasks in the Snow ASVT include: the writing of a snow mapping and runoff prediction handbook that will enable non-ASVT participants to benefit from the ASVT experience; the holding of a final snow mapping workshop to report on specific results from each of the ASVT study areas; and the publishing and disseminating of final project, cost/benefit, and workshop reports.

While the Snow ASVT is more than half completed, the Water Management and Control Project is just starting as a new ASVT. The general objective is to provide a quasi-operational test of the utility of Landsat hydrologic land use/surface cover data in hydrologic engineering models employed in flood control/waterworks planning, design, and management. Much of the Landsat investigative results that led to the initiation of this project are covered by Ragan (1977). The prime cooperator on the project is the U. S. Army Corps of Engineers (Corps) with the investigation centered at the Hydrologic Engineering Center in Davis, California. The Corps typically performs studies on 75 watersheds each year that require model calibration using land use data to eventually produce flood hydrographs for planning. About one quarter of the total calibration effort is spent for land use classification. If Landsat can reduce expenditures for this classification and if the data produced are adequate for the modelling purposes, then significant cost savings could result. This is what the Corps will test in the Water ASVT.

The definition phase of the Water ASVT has been completed in which Landsat hydrologic land use classifications on two watersheds, Trail Creek in Georgia and Castro Valley in California, familiar to the Corps were compared to existing conventional land use information. Landsat classifications were acceptable and the results led to the actual test phase which is beginning now. In this phase the Corps will pick three additional watersheds on which the timeliness, accuracy, costs, manpower, labor-saving, and model compatibility aspects of the Landsat data will be evaluated. The land use classification on the first of these watersheds will be done using computer processing of Landsat digital data by the Corps contractor, the University of California, Davis (UCD). The second watershed will be classified by both the Corps and UCD, and the third watershed will be done primarily by Corps personnel. The successful aspects of the Landsat-based technology will be adopted by the Corps, put on their computational facilities, and transferred to District Offices through training courses at the Hydrologic Engineering Center. Care will be taken during the test phase to collect data, document procedures, and total costs so that a well-founded comparison between Landsat and conventional procedures can be made. These data will be used in a cost/benefit study similar to that being conducted in the Snow ASVT.

The test phase of the Water ASVT should be completed by December 1977 and the transfer phase should be finished by December 1978 or early 1979. Final project reports, cost/benefit documents, and workshops should be completed at the end of the transfer phase.

Additional ASVT's in water resources are expected to result as the remote sensing technology is further refined. Because of initial investigative results, certain areas stand out as potential future ASVT candidates. The survey of irrigated lands has been shown to be relatively straightforward and actually a specific kind of hydrologic land use study. It appears that information on the acreage under irrigation, a basic classification of general crop types

undergoing irrigation, and the type of irrigation being practiced may be obtainable from Landsat. An ASVT on this topic could be expected by 1978. Results from floodplain mapping using Landsat have been very promising (Sollers, Rango, and Henninger, 1977), however, the lack of required resolution has been the major drawback. When a much improved resolution and multispectral coverage is combined on Landsat-D, an ASVT in floodplain mapping could result by 1981. Advances in soil moisture monitoring using thermal infrared and microwave data have been impressive using aircraft data. Further refinements of methods and appropriate sensors on spacecraft should permit a soil moisture ASVT to go forward by 1984. Although extremely early in the developmental stage now, snow water equivalent monitoring with microwaves shows definite promise. Assuming research continues to provide positive results, microwave snow models are developed, and adequate resolution sensors are available, a snow water equivalent ASVT should begin by 1987. Other ASVT's in this time period are definite possibilities as new research results and water management needs dictate.

6. NEW SYSTEMS

Although substantial advances have been made in terms of employing visible and infrared remote sensing, as previous paragraphs have indicated, there are some obvious areas where improvement is needed. Table 3 provides a list of sensors and systems, plus brief descriptions of their characteristics, that are planned or have been considered for implementation in the late 1970's or the 1980's. The principle observing needs, insofar as visible and infrared systems are concerned, include requirements for higher spatial resolution and frequency of observations. Higher spectral resolution is also needed to better identify certain materials and eliminate errors in classification.

New spacecraft systems of note employing improved visible and infrared observation capabilities include the Landsat-D Thematic Mapper (TM) system scheduled for operation in 1981, the TIROS-N observing system scheduled for initial operation in 1978, and the Heat Capacity Mapping Mission (HCMM) scheduled for launch in 1978. The Landsat-D will be a "second-generation" earth resources satellite system that will offer substantial spatial resolution and spectral band improvements. The 30 meter resolution should be much more applicable to floodplain mapping and the delineation of inland wetlands. As an example of the advantages afforded by the increased spectral bands capabilities, the 1.55-1.75 μm band will be most useful in separating clouds from snow in TM scenes. The TIROS-N system Advanced Very High Resolution Radiometer (AVHRR) will eventually provide 6 hour global coverage by using two satellites and thereby provide a step forward in terms of better meeting frequency of coverage requirements. The HCMM mission involves utilizing an orbit configuration that will permit the acquisition of diurnal temperature range information. This diurnal temperature range information has been found to be related to soil moisture and, more generally, the thermal inertia properties of various materials. Other ideas that have been considered include the implementation of near-Landsat observing capabilities on a geosynchronous platform (sometimes called the Synchronous Earth Observatory System - SEOS). This would provide the ultimate system insofar as frequency of coverage is concerned. Another idea of merit is that of developing a pointable observing system with a very high spatial resolution capability in the 10-15 meter range. This would allow viewing of slowly changing situations where high resolution is needed (e.g. hydrologic land use), or views of "targets-of-opportunity" where high spatial resolution is needed such as flooded areas, while reducing the data processing problem to manageable proportions. Further time and study will be necessary in order to determine if the investment necessary to implement these systems is warranted.

Visible and infrared systems are limited by cloud cover and their inability to penetrate materials such as snow, soil, and vegetation. Microwave observations can penetrate cloud cover and other media and these observations are sensitive to changes in the dielectric properties of materials. The dielectric properties of soil and snow are primarily a function of water content. These characteristics of microwave observations dictate that a water resources/hydrology remote sensing program should investigate thoroughly the applicability of microwave observations. Progress along this line of endeavor is described by Ulaby (1977). Table 3 indicates that several systems involving active and passive microwaves are scheduled for the not-to-distant future that will provide some very interesting data for remote sensing applications research.

7. CONCLUSIONS

Substantial progress has been made in meeting the requirements of the water resources management/hydrology communities as expressed, for example, by the World Meteorological

Organization. Visible and infrared observing capabilities on spacecraft are applicable where the monitoring of snowcovered area, hydrologic land use, and the area and near-surface layer turbidity of water bodies are considered to be important. Because of success in quantifying the information content of remotely-sensed observations and demonstrating their utility in watershed models, the transfer of technology process is continuing in quasi-operational tests concerning the use of the Landsat system and the monitoring of snowcover area and hydrologically-relevant land use. Improved spaceborne observing systems are expected to be in operation in 1981 that should increase the applicability of visible and infrared remote sensing. In terms of new areas of applications research the microwave portion of the electromagnetic spectrum appears to offer substantial potential for providing fundamental hydrologic measurements.

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REMOTE SENSING APPLICATIONS DEVELOPMENT FOR WATER RESOURCES

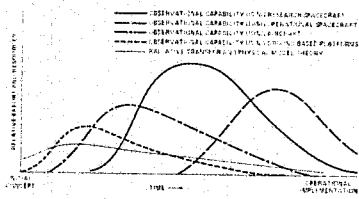
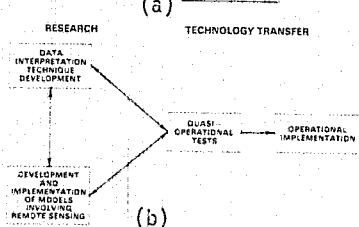
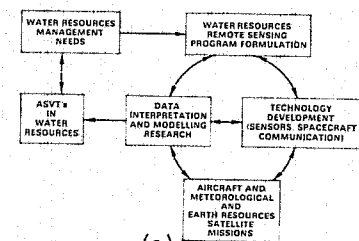


Figure 1

SELECTED HIGH ALTITUDE AIRCRAFT AND SPACECRAFT SYSTEMS AVAILABLE AND APPLICABLE FOR WATER RESOURCES MONITORING AND HYDROLOGICAL STUDIES

VEHICLE/SENSOR	SPECTRAL BANDS	NOMINAL SPATIAL RESOLUTION	APPROPRIATE IMAGE/SCENE AREAL COVERAGE	FREQUENCY OF COVERAGE	PERIOD OF DATA AVAILABILITY	DATA CENTER
OPERATIONAL						
NOAA/VHRR	0.6 - 0.7 μm 10.5 - 12.5 μm	0.9 KM	SUB-CONTINENT	1/DAY - VISIBLE 2/DAY - I.R.	1972 TO PRESENT	SUITLAND, MD
ESSA NOAA/AVCS-SR	VISIBLE (AVCS) 0.6 - 0.7 μm (SR) 10.5 - 12.5 μm	4 KM	SUB-CONTINENT	1/DAY - VISIBLE 2/DAY - SR	1966 PRESENT	SUITLAND, MD
SMS-GOES/VISSR	0.6 - 0.7 μm 10.5 - 12.5 μm	1 KM	1/3RD OF GLOBE (WESTERN HEMISPHERE)	SEVERAL TIMES PER DAY	1974 PRESENT	SUITLAND, MD
QUASI-OPERATIONAL						
LANDSAT 1, 2/MSS	0.5 - 0.6 μm 0.6 - 0.7 μm 0.7 - 0.8 μm 0.8 - 1.1 μm	80 M	34,000 KM ²	ONCE EVERY 18 DAYS (8 DAYS WITH TWO SATELLITES)	1972-PRESENT	SIoux FALLS, S.D. SUITLAND, MD SALT LAKE CITY, UT
HIGH ALTITUDE NASA AIRCRAFT	VISIBLE AND INFRARED PHOTOGRAPHY	10 METERS (APPROX)	400 - 900 KM ²	VARIABLE	OCCASIONAL COVERAGE IN SELECTED AREAS FOR 10 YEARS OR MORE	SIoux FALLS, S.D.
RESEARCH AND DEVELOPMENT						
SKYLARK EREP: MULTISPECTRAL CAMERAS, SPECTROMETERS	VISIBLE AND NEAR INFRARED, THERMAL INFRARED	10 - 70 M	10,000 - 30,000 KM ²		1973, 1974 (THREE FLIGHTS)	SIoux FALLS, S.D. SUITLAND, MD SALT LAKE CITY, UT
SKYLARK EREP: MICROWAVE SCATTEROMETER RADIOMETER	13.9 GHz	11 KM	0-48° INCIDENCE ANGLES	VARIABLE	1973, 1974	SIoux FALLS, S.D. SUITLAND, MD SALT LAKE CITY, UT
L BAND RADIOMETER	1.4 GHz	124 KM	—	VARIABLE	1973, 1974	
NIMBUS 1-6	MULTISPECTRAL RADIOMETERS	4 - 55 KM	SUB-CONTINENT	DAILY IN SELECTED PERIODS	DISCONTINUOUS COVERAGE SINCE 1964	GREENBELT, MD
NIMBUS 5, 6/ MICROWAVE RADIOMETERS	1.55 GHz 0.86 GHz	30 KM	SUB-CONTINENT	DAILY	DISCONTINUOUS COVERAGE SINCE 1972	GREENBELT, MD

Table 1

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DATA REQUIREMENTS FOR SATELLITE REMOTE SENSING
(WORLD METEOROLOGICAL ORGANIZATION, 1976)

HYDROLOGICAL ELEMENT	RESOLUTION ¹ A B C	ACCURACY ²	FREQUENCY ³	HYDROLOGICAL ELEMENT	RESOLUTION ¹ A B C	ACCURACY ²	FREQUENCY ³
10 SHOW UNLAND				51 SOIL PROPERTIES			
11 DRAINAGE	30 100 1000	±5% (SHOW AREA)	DAILY	51.1 SOIL TYPE	100 1000 1000	±5%	1 YEARLY
12 DRAINAGE	300 1000 10000	±5% (SHOW AREA)	DAILY	51.2 MOISTURE CONTENT PROFILE	100 1000 1000	±5%	1 YEARLY
13 WATER EQUIVALENT	10 300 1000	±2 mm ± 2 in	DAILY	51.3 MOISTURE & TEMPERATURE	100 1000 1000	±5%	1 YEARLY
14 FREE WATER CONTENT	100 300 1000	±10% ± 2 in	DAILY	51.4 TEMPERATURE PROFILE	100 1000 1000	±5%	1 YEARLY
15 WATER EQUIVALENT & TEMP	10 300 1000	±10% ± 2 in	DAILY	51.5 MOISTURE & TEMPERATURE	100 1000 1000	±5%	1 YEARLY
16 SURFACE ALBEDO	100 300 1000	±5%	DAILY	51.6 DEPTH OF DECAHEDRAL FROST	100 1000 1000	±5%	1 YEARLY
20 LAKE AND RIVER				51.7 DECAHEDRAL FROSTING	100 1000 1000	±5%	1 YEARLY
21 ICE LENS	30 100 1000		DAILY	60 GRASS/VEGETATION (1000)	100 1000 1000	±5%	1 YEARLY
22 AREA OF CONTINUOUS ICE COVER	300 1000 10000	±2%	DAILY	60.1 GRASS/VEGETATION (1000)	100 1000 1000	±5%	1 YEARLY
23 CLIMATE REGION	10 30 300		DAILY	60.2 GRASS/VEGETATION (1000)	100 1000 1000	±5%	1 YEARLY
24 ICE MOVEMENT	10 30 300		DAILY	60.3 GRASS/VEGETATION (1000)	100 1000 1000	±5%	1 YEARLY
25 TYPE OF STRENGTH	30 100 1000		DAILY	60.4 GRASS/VEGETATION (1000)	100 1000 1000	±5%	1 YEARLY
26 THICKNESS	10 30 300	±2 mm ± 2 in	DAILY	60.5 GRASS/VEGETATION (1000)	100 1000 1000	±5%	1 YEARLY
27 ICE SURFACE TEMP	30 100 1000	±10% ± 2 in	DAILY	60.6 GRASS/VEGETATION (1000)	100 1000 1000	±5%	1 YEARLY
30 GLACIERS				70 GRASS/VEGETATION (1000)	100 1000 1000	±5%	1 YEARLY
31 INVENTORY	30 100 300	±5%	1 YEARLY	70.1 GRASS/VEGETATION (1000)	100 1000 1000	±5%	1 YEARLY
32 SNOW COVERED AREA	100 300 1000	±5%	1 YEARLY	70.2 GRASS/VEGETATION (1000)	100 1000 1000	±5%	1 YEARLY
33 LENGTH VARIATION	10 30 100	±5%	1 YEARLY	70.3 GRASS/VEGETATION (1000)	100 1000 1000	±5%	1 YEARLY
34 LENGTH VARIATION	10 30 100	±5%	1 YEARLY	70.4 GRASS/VEGETATION (1000)	100 1000 1000	±5%	1 YEARLY
35 MONITORING SURGES	30 100 300	±5%	1 YEARLY	70.5 GRASS/VEGETATION (1000)	100 1000 1000	±5%	1 YEARLY
40 SURFACE WATER				80 SURFACE WATER			
41 SATURATED SOIL AREA	10 30 100	±5%	1 YEARLY	80.1 SURFACE WATER	100 1000 1000	±5%	1 YEARLY
42 SATURATED SOIL AREA	10 30 100	±5%	1 YEARLY	80.2 SURFACE WATER	100 1000 1000	±5%	1 YEARLY
43 SURFACE WATER	10 30 100	±5%	1 YEARLY	80.3 SURFACE WATER	100 1000 1000	±5%	1 YEARLY
44 SURFACE WATER	10 30 100	±5%	1 YEARLY	80.4 SURFACE WATER	100 1000 1000	±5%	1 YEARLY
45 LAKE OR RIVER SURGE				90 SURFACE WATER			
				90.1 SURFACE WATER	100 1000 1000	±5%	1 YEARLY
				90.2 SURFACE WATER	100 1000 1000	±5%	1 YEARLY
				90.3 SURFACE WATER	100 1000 1000	±5%	1 YEARLY
				90.4 SURFACE WATER	100 1000 1000	±5%	1 YEARLY
				90.5 SURFACE WATER	100 1000 1000	±5%	1 YEARLY
				90.6 SURFACE WATER	100 1000 1000	±5%	1 YEARLY
				90.7 SURFACE WATER	100 1000 1000	±5%	1 YEARLY
				90.8 SURFACE WATER	100 1000 1000	±5%	1 YEARLY
				90.9 SURFACE WATER	100 1000 1000	±5%	1 YEARLY
				90.10 SURFACE WATER	100 1000 1000	±5%	1 YEARLY
				90.11 SURFACE WATER	100 1000 1000	±5%	1 YEARLY
				90.12 SURFACE WATER	100 1000 1000	±5%	1 YEARLY
				90.13 SURFACE WATER	100 1000 1000	±5%	1 YEARLY
				90.14 SURFACE WATER	100 1000 1000	±5%	1 YEARLY
				90.15 SURFACE WATER	100 1000 1000	±5%	1 YEARLY
				90.16 SURFACE WATER	100 1000 1000	±5%	1 YEARLY
				90.17 SURFACE WATER	100 1000 1000	±5%	1 YEARLY
				90.18 SURFACE WATER	100 1000 1000	±5%	1 YEARLY
				90.19 SURFACE WATER	100 1000 1000	±5%	1 YEARLY
				90.20 SURFACE WATER	100 1000 1000	±5%	1 YEARLY
				90.21 SURFACE WATER	100 1000 1000	±5%	1 YEARLY
				90.22 SURFACE WATER	100 1000 1000	±5%	1 YEARLY

Table 2

PLANNED OR CONSIDERED SPACECRAFT MISSIONS
THAT WOULD HAVE FEATURES RELEVANT
TO HYDROLOGY AND WATER RESOURCES

VEHICLE/SENSOR	SPECTRAL BANDS	SPATIAL RESOLUTION	IMAGE SENSOR AREA/AL COVERAGE	REPEAT INTERVAL	REMARKS
PLANNED	0- 0.5 μ m 0.5- 0.7 μ m 0.7- 0.9 μ m 0.9- 1.1 μ m 1.1- 1.3 μ m	80 μ m	105 X 185 km	10 DAYS	BASIC INFORMATION COVER EXHAUSTIVE AS TO THE IMAGE QUALITY AND SYSTEM PRODUCTION CAPABILITY AT RESOLUTION
LANDSAT 4 MSS 1978	0.45 0.62 μ m 0.65 0.80 μ m 0.85 0.88 μ m 1.05 1.00 μ m 1.65 1.25 μ m	240 μ m	125 X 185 km	16 DAYS	SECOND GENERATION HIGH RESOLUTION SATELLITE SYSTEM
LANDSAT 4 THERMAL MAPPER 1978	0.8 GHz 2.1 GHz 3.6 GHz 23.2 GHz 39 GHz	82 X 144 km 97 X 84 km 34 X 53 km 29 X 43 km 17 X 20 km	1000 km ORBIT	~ 1 DAY	
NAVSTAR 1A MMH 1978					
SPASAT 4 MMH 1978	(See NAVSTAR 1A)				
SPASAT 4 SAT 1978	1.5 GHz	25 m	100 km ORBIT	(See REFERENCE)	WORK ON ORBITAL CHARACTER EVALUATION AND SYSTEM THEME FOR THE PROPOSED MISSION
TELESTAR 4A SRR 1978	0.55 0.8 μ m 0.85 1.0 μ m 1.05 1.1 μ m 1.05 3.5 μ m	1.1 4.5 km	500 X 400 km	12-24 HOURS	TELESTAR 4A SATELLITE MISSION
HEMIS 4 MMH 1978	0.5- 1.1 μ m 0.5- 1.25 μ m	500 m	700 km ORBIT	SEVEN	HEMIS 4A COMMISSIONED SO THAT IT CAN PROVIDE A 1000 METER RESOLUTION 22 X 400 KM AREA AT LEAST
CONSIDERED	LANDSAT CSP PROMISES AND IMPROVEMENT ON LANDSAT FLIGHTS	25-100 m	100-300 km ORBIT	7-10	- RECENTLY COMPLETED RESEARCH ON THE NEW SATELLITE SYSTEMS FOR THE LANDSAT 4A SATELLITE MISSION IN 1978 TIME FRAME
HEMIS 4A SRR 1978	LANDSAT RADIOMETER K IN BAND	~ 35-120 m ~ 20 km	100-300 km ORBIT ~ 7000 km	1-6 DAYS 1 DAY	HEMIS 4A SATELLITE MISSION IN 1978 TIME FRAME LANDSAT 4A SATELLITE MISSION IN 1978 TIME FRAME
MULTI-CHANNEL ECHO MICROWAVE 1980S	LANDSAT RADIOMETER K IN BAND	~ 35-120 m ~ 20 km	100-300 km ORBIT ~ 7000 km	1-6 DAYS 1 DAY	HEMIS 4A SATELLITE MISSION IN 1978 TIME FRAME LANDSAT 4A SATELLITE MISSION IN 1978 TIME FRAME
GEOSYNCHRONOUS SATELLITE 1980S	LANDSAT RADIOMETER K IN BAND	100-500 km	LOCAL TO SUB-CONTINENT AREAS	PRECISION OF ARC	ONLY ONE RESEARCHING IN 1978 TIME FRAME
RESEARCH IN PROGRESS ON FIXABLE ORBITING SYSTEMS	LANDSAT RADIOMETER K IN BAND	50-150 m	WORLDWIDE AREAS	ONLY ONE RESEARCHING IN 1978 TIME FRAME	ONLY ONE RESEARCHING IN 1978 TIME FRAME

Table 3

MICROWAVE REMOTE SENSING OF HYDROLOGIC PARAMETERS

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ABSTRACT

A perspective on the implementation of microwave sensors in future airborne and spaceborne observations of hydrologic parameters is presented. The rationale is based on a review of the status and future trends of active (radar) and passive (radiometer) microwave research as applied to the remote sensing of soil moisture content, snowpack water equivalent, freeze/thaw boundaries, lake ice thickness, surface water area, and the specification of watershed runoff coefficients. Included are analyses and observations based on data acquired from ground based, airborne and spaceborne platforms and an evaluation of advantages and limitations of microwave sensors.

1. INTRODUCTION

Among the electromagnetic windows available to satellite remote sensing of the earth's surface, the microwave window is particularly suited to the monitoring of hydrologic parameters. From the standpoint of requirements that should be met by an operational remote sensing system designed to provide useful hydrologic information, microwave sensors can provide the following:

- a) Sensitivity to Wetness: Liquid water is by far the most influential single terrain parameter in the terrain-microwave interaction process. The backscattering coefficient, σ^0 , and emissivity, ϵ , characterizing respectively the radar and radiometer responses, are, in general, governed by the geometrical and electrical properties of the terrain under investigation. Because of the high microwave permittivity of liquid water relative to that of dry matter, the permittivities of soil, vegetation and snow are strongly dependent on their water contents. This dependence on water content influences in turn the scattering, absorption and emission properties of terrain, as discussed in more detail in Section 2.
- b) Weather Independence: The ability to make timely observations unhampered by cloud cover is important to most hydrologic applications; examples include the delineation of flooded areas while flooding is in progress and the monitoring of soil moisture, snowpack wetness and the movement of the freeze-thaw boundary on a regular repetitive basis so that the information can be fed into appropriate watershed runoff prediction models for water resources management. A simple example is provided in Table 1 to illustrate the insensitivity of microwaves to clouds; whereas the transmissivity through a one Km thick cloud characterized by a visibility of 610 m is approximately 0.001 in the visible band and 0.25 in the infrared band, the transmissivity is higher than 0.99 in the commonly used part of the microwave spectrum ($\lambda \geq 3.6$ mm).

TABLE 1. COMPARISON OF VISIBLE, INFRARED AND MICROWAVE ATTENUATION (dB/Km) AND TRANSMITTIVITY OF A 1 Km THICK WATER CLOUD WHOSE OPTICAL VISIBILITY IS 610 m [1].

Parameter	Visible (0.6 μ m)	Infrared (10 μ m)	M i c r o w a v e		
			(3.2 mm)	(8.6 mm)	(7.5 mm)
Attenuation (dB/Km)	30	6	0.13	2.2×10^{-2}	3×10^{-4}
Transmissivity of 1 Km Thick Cloud	0.001	0.25	0.97	0.99	0.99

- c) Spatial Resolution: The spatial resolution capability of a passive microwave sensor is dictated by the altitude of the platform and the antenna beamwidth, the latter being governed by the ratio of the wavelength to the antenna size. Hence the utility of microwave radiometers is limited to applications whose spatial resolution requirements are of the order of tens of kilometers; as examples, the ground resolution at nadir was 25 Km for the 1.55 cm wavelength Electronically Scanning Microwave Radiometer (ESMR) flown aboard Nimbus 5 and 15.5 Km and 117 Km for the 2.16 cm and 21.4 cm wavelength radiometers flown aboard Skylab, respectively. Active microwave imaging systems, on the other hand, can provide fine resolution imagery (from satellite altitudes) compatible with the requirements for monitoring flooded areas, drainage basin characteristics, and soil moisture variations over small watersheds or fields.

Among the sensors to be flown on SEASAT-A in 1978 is a 22 cm wavelength (L-Band) synthetic aperture imaging radar capable of producing wide swath imagery with a spatial resolution of 25 m or better. Similar specifications are currently under consideration for a dual-frequency imaging radar to be used on selected shuttle flights to evaluate its capabilities for land applications.

2. STATUS REVIEW

The objective of this section is to evaluate the response of active and passive microwave sensors to key hydrologic parameters, and hence assess their utility for water resources. Ample documentation of the general physical principles governing emission and scattering by terrain is now available in several texts and manuals [1-3], along with the engineering design and construction considerations associated with the implementation of radar and radiometer systems. These aspects are not discussed herein; instead, emphasis is placed on the major developments in microwave research as applied to hydrology during the past few years. Following a review of these developments, a summary chart will be provided for easy reference.

2.1 SOIL MOISTURE

Soil Moisture content is a fundamental parameter of the earth's environment; it is a key input into numerous agricultural, hydrologic and meteorological models including crop yield prediction, flood forecasting, runoff prediction for assessing watershed yield and planning and reservoir management models, among others.

The strong sensitivity of the microwave backscattering coefficient σ^0 and emissivity ϵ to soil moisture variation has been well demonstrated by numerous investigations [4-21] at a variety of wavelengths, angle of incidence and

polarizations. The accuracy with which soil moisture can be estimated, however, is subject primarily to two other natural variables, soil surface roughness and vegetation cover, and to a lesser extent, to soil type. Hence, the objective of microwave investigations of soil moisture during the past decade has been to ascertain the optimum combination of sensor parameters (wavelength(s), angle of incidence range and polarization(s)) for minimizing the effects of surface roughness and maximizing penetration through vegetation while maintaining good sensitivity to soil moisture content. An additional objective has been to establish an estimate of the effective depth of the soil surface layer that is responsible for the observed microwave backscatter or emission so that an estimate of the total water within a given soil column can be made.

Passive Microwave

The passive microwave response to soil moisture has been extensively investigated from ground-based and airborne platforms and to a limited extent, from spaceborne platforms. The effect of surface roughness on the emissivity of bare soil was investigated by Blinn and Quade [14] who after measuring the radiometer response to soil moisture of smooth surfaces at 1.42 GHz, 10.69 GHz and 31.4 GHz (21 cm, 2.8 cm and 0.95 cm wavelengths, respectively), they measured the response as a function of furrow spacing for fixed moistures. Their results indicate that the emissivity ϵ increases with furrow spacing and that the rate of increase of ϵ with furrow spacing is the smallest at the longest wavelength investigated. Also, among the two polarizations employed in their measurements (Horizontal and Vertical), the horizontally polarized emissivity was slightly less sensitive to furrow spacing. A similar set of experiments were conducted by Texas A&M University [18] at 1.42 GHz and 10.69 GHz. The antenna temperature of bare as well as vegetated fields was measured as a function of moisture content for each of three different surface roughness conditions. The 1.42 GHz data indicate strong sensitivity to moisture for each of the surface roughness conditions individually, as well as to the combined data, although with a lower correlation. Figure 1 depicts the response of the antenna temperature (normalized to the 0-1 cm soil thermometric temperature) to equivalent soil moisture as defined by Newton [18].

The data shown cover a wide range of soil surface roughness, from an extremely smooth surface to a very rough (plowed) soil surface. The spread in the normalized antenna temperature is attributed to surface roughness. A radiative transfer model developed by Burke and Paris [22] suggests that the effects of surface roughness can be partially removed through the use of the sum and difference of the horizontally and vertically polarized emissivities. Recent analyses of ground-based data by Newton [18] as well as an analysis reported by Schmugge et al. [23] of airborne data confirm the potential utility of the Burke and Paris approach. Additional data are required before a thorough evaluation of the model can be made, however.

Aircraft observations of the emissivity response to soil moisture have been made both in the U.S. [19,20,23] and in the Soviet Union [24,25]. The aircraft results confirm the ground-based observations that longer wavelengths are preferable for the remote sensing of soil moisture because of their lower sensitivity to surface roughness and greater capability to penetrate through vegetation canopies. Schmugge [20] reports that the 1.55 cm wavelength microwave scanning radiometer data acquired during three flights in 1972 indicate that the microwave emissivity of heavy soils (high clay content) exhibits a considerably weaker sensitivity (slope) to moisture content by weight than the emissivity of light soils. The dependence on soil type was then removed by expressing soil moisture content in units of percent of field capacity of the soil. Determination of field capacity of a given field was accomplished through the use of the following empirical relation generated by Schmugge [20]:

$$\text{Field Capacity} = 25.1 - 0.21 \times \text{SAND} + 0.22 \times \text{CLAY} \quad (1)$$

where SAND and CLAY represent their respective soil fractions in percent. Figure 2 is a plot of 21 cm brightness temperature data as a function of moisture content in the top 1 cm of the soil expressed as a percent of field capacity [20]. The data includes airborne measurements of bare fields made during 1972 and 1973

flights over agricultural test sites around Phoenix, Arizona and in the Imperial Valley of Southern California.

It should be pointed out that part of the scatter observed in Figures 1 and 2 and in succeeding figures depicting the microwave (active or passive) response to soil moisture is due to uncertainty in the soil moisture "ground-truth" determination. In most cases, the average of a few soil samples (typically four) is used to characterize the moisture content of the field under observation. Soil surface configuration and soil texture inhomogeneity can cause large spatial variations in moisture content across a given field [23,26]; the coefficient of variability can be as high as 0.5 for the top 1 cm layer of the soil. Thus characterizing the moisture of an entire field by the average of a few sample points can introduce considerable error. Because soil moisture is a dynamic variable, it is essential that the soil samples be acquired during a very short interval, approximately contemporaneous with the microwave observations. Hence the number of samples acquired in support of the microwave observations is usually a compromise between the spatial and temporal variability considerations.

Several radiative transfer models [8,22,27] have been applied to estimate the effective depth of the soil layer responsible for the observed sensor (passive and active microwave) response. Although the various predictions do not agree quantitatively, researchers in this field agree with the qualitative theoretical predictions which state that penetration depth (of the soil) a) decreases with moisture content and b) increases with wavelength. According to Schmugge [20] and Batlivala and Ulaby [9], the observed sensor response (σ^0 or ϵ) under most natural conditions is due to moisture in a surface layer whose thickness varies (inversely with moisture content) between 0.1 and 0.3 of the sensor wavelength. Newton [18] predicts a wider range extending between 1 cm (0.05λ) and 21 cm (1λ) at 21 cm wavelength. In either case, for applications where estimates of the moisture content at deeper layers are needed (such as for crop yield prediction models), the soil moisture in the top surface layer, as measured by a microwave sensor, has to be used in combination with soil moisture budget models to provide estimates at greater depths.

A vegetation canopy is a lossy dielectric which acts as an attenuator of the radiation emitted by the underlying soil as well as a self emitter. Field measurements [18] as well as airborne observations [20] show that the effects of the vegetation cover can be minimized by operating at the longer wavelengths in the microwave region. In Figure 3 [20] airborne observations of the brightness temperature of vegetated fields (small grains and alfalfa up to 20 cm high) at wavelengths of 21 cm and 1.55 cm are compared; the longer wavelength radiometer is clearly superior in terms of its response to soil moisture as evidenced by the steeper slope and the smaller degree of scatter of the data points around the regression line.

Because of the poor spatial resolution capabilities of microwave radiometers, it has been difficult to evaluate the performance of spaceborne passive microwave sensors so far as their sensitivity to soil moisture is concerned. Eagleman [28] reports very high correlation coefficients (≥ 0.95) between the brightness temperature as measured by the 21 cm and 2.1 cm wavelength radiometers flown aboard Skylab in 1973 and soil moisture content in the surface 2.5 cm. The results cannot be considered conclusive, however, because of the poor representation of the moisture in the large ground footprints (approximately 10,000 Km² and 200 Km² for the 21 cm and 2.1 cm radiometers, respectively) by a few soil samples.

In a separate study reported by Schmugge et al. [29], a brightness temperature contour map (Figure 4) was generated with ESMR data for the Mississippi Valley following a period of heavy rain over the area in July 1973. The region of low brightness temperature (shaded in Figure 4) is the relatively flat land on either side of the river which corresponds to an outwash aquifer where unconsolidated sand and gravel deposits are capable of storing large amounts of ground water. Thus, for gross resolution mapping of soil moisture, passive microwave sensors can be very valuable.

Active Microwave

The radar response to soil moisture content has been extensively investigated by the University of Kansas [4-10] using a truck mounted 1-18 GHz (30-1.67 cm wavelength, respectively) Active Microwave Spectrometer (MAS) system. The sensitivity to soil moisture content and the accuracy with which it could be estimated were evaluated for both bare and vegetation-covered fields. The objective of the bare field experiments was to determine the optimum radar parameters (wavelength, angle of incidence range and polarization configuration) for minimizing the response to surface roughness while retaining strong sensitivity to moisture content.

Bare field experiments were conducted in two consecutive years, 1974 and 1975. Each of the two experiments examined the radar response to soil moisture of several fields with considerably different surface roughness conditions. A notable difference between the two experiments, however, was soil type; the 1974 experiment was conducted on fields with high clay content (49%) whereas the 1975 fields contained only 17% clay. Although both experiments provided identical answers in terms of optimum radar parameters for sensing soil moisture content--microwave frequency around 4.75 GHz ($\lambda = 6.3$ cm) and 7° - 17° angle of incidence range (relative to nadir)--the observed sensitivity of σ° to moisture content was somewhat different for the two experiments (Figure 5). Upon converting moisture content from volumetric moisture content to percent of field capacity, which incorporates the soil textural differences, the sensitivities became almost identical (Figure 6).

This approach was adapted from Schmugge [20] according to Equation 1. The calculated linear correlation coefficient between the radar backscattering coefficient σ° and percent of field capacity for the combined 1974 and 1975 data is 0.84. Considering the uncertainty associated with the measurement of σ° (standard deviation $\approx \pm 0.9$ dB relative to the mean) and the uncertainty associated with the measurement of moisture content (standard deviation as high as ± 0.5 relative to the mean), the results are statistically very significant.

In addition to providing optimum sensor parameters for sensing soil moisture with radar, the University of Kansas investigation included a comparative analysis of the performance of different system configurations by evaluating the uncertainties associated with the estimation of soil moisture by an active microwave sensor due to such factors like surface roughness and surface slope. For example, a wavelength of 25 cm is preferred to the proposed 6.3 cm wavelength so far as penetration through vegetation is concerned, but the data acquired at 25 cm wavelength show that the correlation between σ° and moisture content is inferior to the correlation at 6.3 cm wavelength (0.70 compared to 0.84). Moreover, σ° at 25 cm is far more sensitive to angle of incidence variations than σ° at 6.3 cm, which would result in larger errors in the predicted soil moisture value due to the uncertainty in the assumed value of surface slope.

From an operational standpoint, it is desirable to characterize the sensor performance in terms of its capability to classify soil moisture correctly into a specified number of moisture intervals. The results of such a test (Figure 7) indicate that radar can correctly classify moisture into four intervals with 83 percent accuracy [10]. Such a capability far exceeds the current capabilities of optical and infrared sensors (even under clear sky conditions) as well as the predictions of conventional techniques based on climatological data.

The above results have not yet been confirmed from airborne or spaceborne platforms due to the lack of radar systems operating at the wavelength determined as optimum (6.3 cm) by the ground-based systems. NASA/JSC is currently developing a 6.3 cm wavelength airborne scatterometer for conducting soil moisture experiments in 1978.

Having determined the active microwave response to soil moisture for the bare soil case, the University of Kansas study proceeded to examine the effects of vegetation cover. Radar backscatter measurements of fields grown with wheat, milo, soybeans and corn were made as a function of time between May and September, 1975 [9]. It was observed that the correlation coefficient between the

HH-polarized σ° and soil moisture varied between 0.6 for the case where all crop types were included in the analysis to about 0.9 for individual crop types. The HV-polarized data provided a somewhat better correlation with moisture content (0.76) for the all crop case. The use of a two-dimensional vector consisting of HH and HV 4.25 GHz data can correctly classify moisture content of vegetation covered soil (into four intervals) with 80 percent accuracy [10].

Although no detailed airborne investigations have yet been reported of active microwave response to the soil moisture content underneath a vegetation canopy, an observation was made of the difference between dry soil and soil undergoing irrigation in 1971 while conducting radar observations of agricultural fields. During a flight by the NASA/JSC P3A aircraft over a test site near Garden City, Kansas, measurements were acquired by a 13.3 GHz scatterometer from several fields each of which was found (from aerial photography and field crew's reports) to contain sections into which irrigation water was flowing and sections ready for irrigation but not yet wetted [30]. For each of these fields, the effect of the irrigation on the radar return appeared to produce a difference of about 7 dB at angles within 40° from nadir. An example is given in Figure 8 [30] where the measured σ° curves for the irrigated and non-irrigated sections of a corn field are shown. Since all ground conditions, except for soil water content, were similar over the entire field, the differences in σ° can only be attributed to the effect of moisture.

The test site consisted of 706 fields, of which, on the basis of ground truth information, 637 were judged as dry and 19 were judged as wet. Some of the fields in the test site were bare ground while the majority were planted with corn, sorghum, alfalfa, sugar beets and wheat. Figure 9 shows the average σ° curves for each of these two sets as a function of incidence angle [30]. The results clearly demonstrate the capabilities of radar in separating dry terrain from wet terrain under a variety of vegetation cover.

2.2 SNOW WETNESS

Detailed quantitative investigations of the microwave response to snow have been, for the most part, confined to ground-based observations. Dry snow and ice exhibit low loss characteristics in the microwave region which permit considerable penetration at the longer wavelengths (>6 cm). At 21 cm wavelength, for example, only a small change in brightness temperature was observed by Meier and Edgerton [31] between no snow and 1.59 m of dry snow cover over an aluminum plate. In contrast, the 0.8 cm wavelength radiometer showed an increase of over 170 K. Measurements made as a function of snow water equivalent indicated that the 0.8 cm wavelength radiometer is again much more sensitive to snow parameters than the longer wavelength systems. As part of the same study, it was observed that the 0.8 cm wavelength brightness temperature changed by about 70°K between 1000 hours, at which time the snowpack was cold and dry, and 1500 hours by which time over 2 percent of the surface layer was in liquid water form (Figure 10).

Results of active microwave observations of snow confirm the general trends noted above for the passive microwave sensors. Measurements of the scattering coefficient of soil in the 4-30 cm wavelength range with and without a 15 cm layer of dry fresh snow cover indicated no measurable change due to the presence of the snow [32]. For wet snow, σ° indicated a strong sensitivity to snow water equivalent (Figure 11), although it was suspected that σ° was actually responding to the snow liquid water content (which was not measured). In a recent (March 1977) experiment conducted in Colorado, it was confirmed that σ° responds most strongly to liquid water content. Moreover, it was also observed that the angles of incidence away from nadir provide better sensitivity to snow wetness and that the sensitivity increases with microwave frequency. The observed frequency dependence of the snow penetration depth points to the potential use of multi-wavelength microwave sensors to reconstruct the depth profile of the snowpack liquid water content.

This conclusion is supported in part by the semi-quantitative analysis reported by Kunzi et al. [33] who used 31.4 GHz and 22.2 GHz brightness temperature data acquired by the Nimbus-E microwave spectrometer (NEMS) to define spectral signatures for snow, sea ice and land ice in Greenland and Antarctica. Among their findings was the observation that the brightness temperature gradient was always higher than -0.4 K/GHz for land with no snow cover and always lower than -0.4 K/GHz for land surfaces covered with snow. Thus, they conclude that "multifrequency remote sensing can be used to map snow cover over land and ice coverage over water" [33].

2.3 WATERSHED RUNOFF

Storm runoff is an important parameter in the design of dams and flood control structures on watersheds. It is related to several parameters of the drainage basin including basin area, network length, number of stream segments, vegetation cover and land use features, among others. The feasibility of mapping stream networks with imaging radar has been established by several studies [29,35] most notably the study by McCoy [34] which shows that the information content provided by the radar image is equivalent in its level of detail to that of a 1:24,000 topographic map. Figure 12 illustrates the use of multiple look direction to overcome the masking effect of shadows in mountainous areas.

The use of microwave radiometry as a tool to estimate runoff characteristics of watersheds was investigated by Blanchard [36]. The results of data acquired by a 2.8 cm wavelength scanning radiometer flown over eight watersheds near Chickasha, Oklahoma, indicate a strong dependence of the polarized brightness temperature difference (between vertical and horizontal polarizations) on runoff coefficient. A similar investigation was recently conducted by Blanchard with radar, but the data have not yet been completely analyzed.

2.4 SURFACE WATER AND FLOOD MAPPING

Mapping surface water bodies (ponds, lakes, reservoirs, rivers, etc.) is useful under the general framework of water resource management. In the absence of vegetation, the discrimination between water and land surfaces by passive microwave sensors is made on the basis of the large difference in emissivity between water and land at all microwave frequencies. Longer wavelengths are particularly appealing because of their superior vegetation penetration capabilities and because the difference in emissivity between water and land surfaces increases with wavelength. Likewise, radar can always map water bodies; in virtually all cases, water is observed to produce a much lower return (tone) on radar imagery.

The ability of microwave sensors to map flood inundated areas under cloud cover conditions is extremely useful since such a capability can be used for conducting relief efforts, assessing loss of life and property and delineating the extent of the flood plain. Mapping flooded land with radar imagery is illustrated in Figure 13; the image was acquired through a cloud cover while flooding was in progress. On the radar image the rivers and the flooded areas appear black, corresponding to a weak backscatter return.

2.5 LAKE ICE

Imaging radar plays the central role in the all-weather ice information system (known as project Icewarn) currently in use by the Great Lakes Winter Navigation Program [37]. Icewarn assists vessels in navigating both through and around the ice by providing the vessels with 3.2 cm wavelength sidelooking airborne radar (SLAR) images along with interpretative ice charts via a radio communication network (Figure 14). In addition to determining the type, location and aerial extent of the ice cover in the Great Lakes from the SLAR imagery, a 2.8 GHz short pulse non-imaging radar is used to measure ice thickness (with an accuracy of ± 2.5 cm from altitudes up to 2 Km). Project Icewarn was first implemented during the 1974-75 winter season; "for the first time in the history of the Great Lakes, shipping continued year-round" [37]. During August and September of 1976, NASA Lewis Research Center in cooperation with other federal agencies demonstrated the ability of the Ice Information System to provide all-weather ice information to shippers along the North Slope [38].

To evaluate the potential use of SEASAT-A's L-band (22 cm wavelength) imager as a tool to classify arctic lakes, several airborne investigations were conducted during the past five years with L-band and X-band (3.2 cm) imaging radars [39-43]. Particularly significant are the results of a 1976 investigation which included field examination (ice and water thickness, salinity of the ice and water, etc.) of a selected number of lakes on the North Slope of Alaska [43]. Analysis of the imagery in conjunction with the ground truth data revealed that "in all cases the sites that show strong return are not frozen completely to the bottom, while the sites that show weak return are" [43]. The image shown in Figure 15 illustrates this difference in the radar return. Moreover, the differentiation between the two cases is appreciably greater on the longer wavelength (L-band) imagery, which is attributed to the lower conductivity losses of the ice.

3. THE FUTURE

Substantial progress has been realized in the management of water resources by applying remote sensing data acquired by LANDSAT 1 and 2 and NOAA VHRR systems. By employing visible, near infrared, and thermal infrared sensors, the spatial distribution of snow cover, surface water, land use, and flooded areas can be delineated, provided weather conditions permit it. Two very important hydrologic parameters -- soil moisture content and snow wetness -- are not amenable to direct sensing by visible, near infrared, and thermal infrared systems, however, while they are amenable to microwave sensors under both clear and cloud-cover conditions.

According to economic studies conducted to evaluate the annual benefits provided by LANDSAT [44,45] hydrologic applications rank in third place, after vegetation resource management applications and geology. The status of hydrologic applications can be substantially improved through the use of a spaceborne microwave system consisting of multi-frequency passive and active sensors. Because of their inherent poor resolution capabilities, the passive microwave sensors would primarily serve in a complimentary capacity.

The status review presented in the previous section indicates that substantial work is still needed in several areas; proven capability of microwave sensors has been demonstrated in the cases of surface water, lake ice, and drainage basin topography, followed by strong evidence of capability in the areas of soil moisture and snowpack monitoring. Table 2 is a summary of the active microwave system requirements as they pertain to individual water resources parameters or applications. It is a slightly modified version of the table generated by the Microwave Planning Panel of the Active Microwave Users Workshop in August, 1976 [46]. The overwhelming majority of the system requirements given in Table 2 can be met by a dual-frequency dual-polarization imaging radar complemented by a dual-frequency dual-polarization scanning radiometer. The only firm requirement on the longer wavelength radar is set by the soil moisture monitoring application. Table 3 is a proposed system configuration which integrates the requirements of Table 2 (with a certain degree of compromise) with the status of microwave remote sensing research as it pertains to hydrologic parameters. Such a system will not only provide useful information for hydrologic applications, it will also serve other application areas including agriculture, geology and oceanography.

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TABLE 2. ACTIVE MICROWAVE SYSTEMS REQUIREMENTS
FOR WATER RESOURCES APPLICATIONS

Application	Role ¹			Wave-lengths (cm)	Interpretation Resolution (m)		Nadir ² Angle	Polar-ization	Revisit Interval	Status	Comments
	Active Microwave	Passive Microwave	Visible/Infrared		Desire	Accept					
1. SOIL MOISTURE MONITORING	P	P	S	6.3 & 1.6-3	30 30	90 90	7°-17° 40°-70°	HH & HV VV & Cross	1-7 days 7-10 days	SE SE	Unique Capability For Vegetation Identification
2. SNOW FIELD (Equiv. Moisture and Liquid Water) MAPPING	P	C	C	1-3	30	90	40°-70°	CS	2-15 days	UT	Limited Experimentation to Date
				7-30	30	90	5°-20°	HH & HV	3-15 days	UT	
3. WATERSHED											
a) Runoff Coefficient Estimate	P	P	S	3-30	30	90	CS	CS	Seasonal	UT	Limited Experimentation to Date
b) Drainage Pattern	P	N	C	3-30	30	90	40°-70°	Any	Annual	PC	Proven Capability
c) Land Use Mapping	P	N	C	3-30	30	90	40°-70°	Any	Annual	SE	
4. SURFACE WATER, FLOOD & WETLAND MAPPING	P	N	C	Any	10	30	40°-70°	Any	Event Determined	PC/SE	Proven Capability
5. FREEZE/THAW LINE MONITORING	P	C	S	3-30	90	200	CS	CS	3-15 days	UT	Limited Experimentation to Date
6. LAKE ICE CLASSIFICATION	P	N	C	1-3	10	30	40°-70°	Any	1-3 days	PC	Operational Capability
				7-30	10	30	10°-40°	Any	1-3 days	SE	Unique Capability

1. P - Prime Sensor
C - Complementary sensor
S - Supportive Sensor
N - Not needed

2. CS - Cannot be specified at this time.

3. PC - Proven Capability
SE - Strong evidence of capability
PS - Potential suggested by experimentation
PT - Potential suggested by theory or analogy
UT - Under test

TABLE 3. A PROPOSED DUAL-WAVELENGTH ACTIVE/PASSIVE
MICROWAVE SYSTEM FOR WATER RESOURCES APPLICATIONS

Parameter	ACTIVE MICROWAVE		PASSIVE MICROWAVE	
	Long Wavelength SAR (1)	Short Wavelength SAR (1)	Long Wavelength Scanning Radiometer	Short Wavelength Scanning Radiometer
Wavelength	6.3 cm	2 cm	21 cm	3 cm
Nadir Angle Range	7°-20°	40°-70°	As wide a scan as possible (2)	As wide a scan as possible (2)
Polarizations	HH & HV	VV & HH	H & V	H & V
Interpretation Resolution	50 meters	50 meters	(2)	(2)
Revisit Interval	3-7 days	3-7 days	3-7 days	3-7 days

(1) SAR = Synthetic Aperture Radar

(2) Dictated by antenna size, orbit altitude, and other engineering considerations.

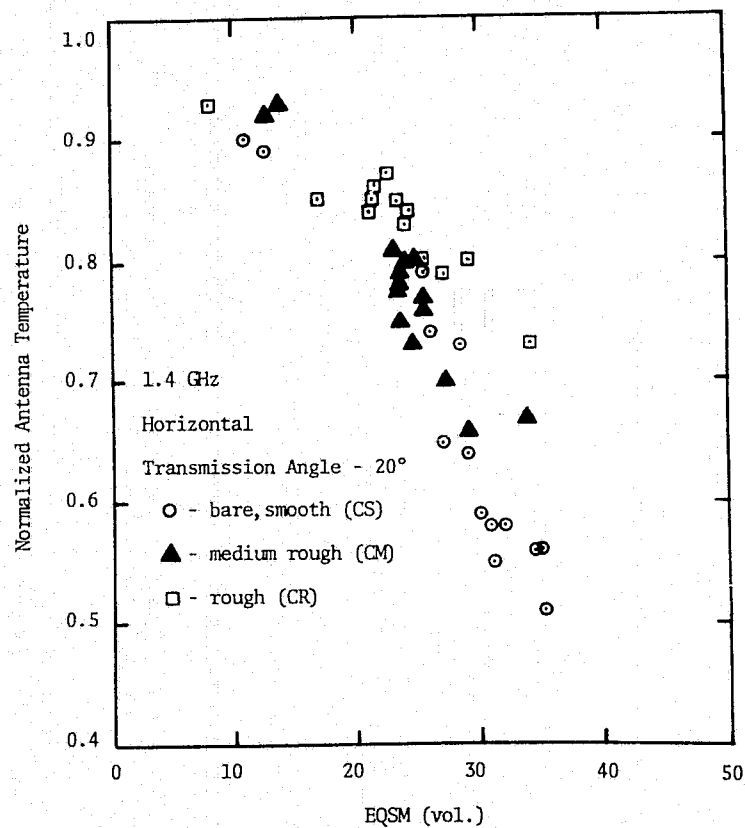


Figure 1: Normalized antenna temperature or bare soil at 1.4 GHz versus Equivalent Soil Moisture Content, Newton [18].

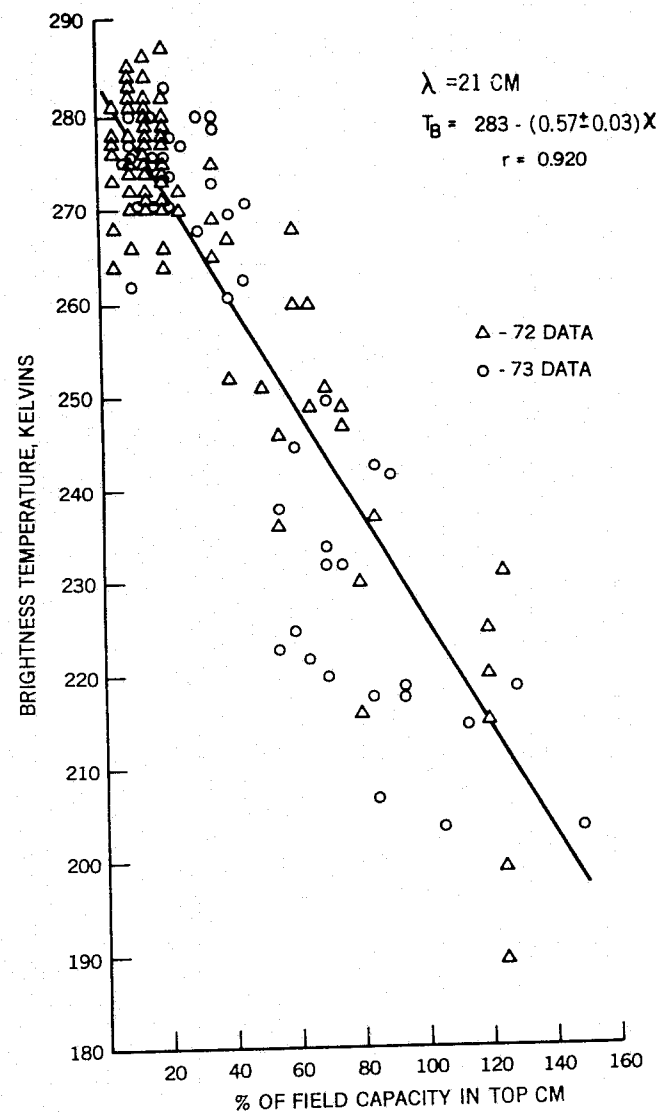


Figure 2: Brightness temperature of bare fields at 21 cm wavelength versus percent of field capacity in the top 1 cm soil layer [20].

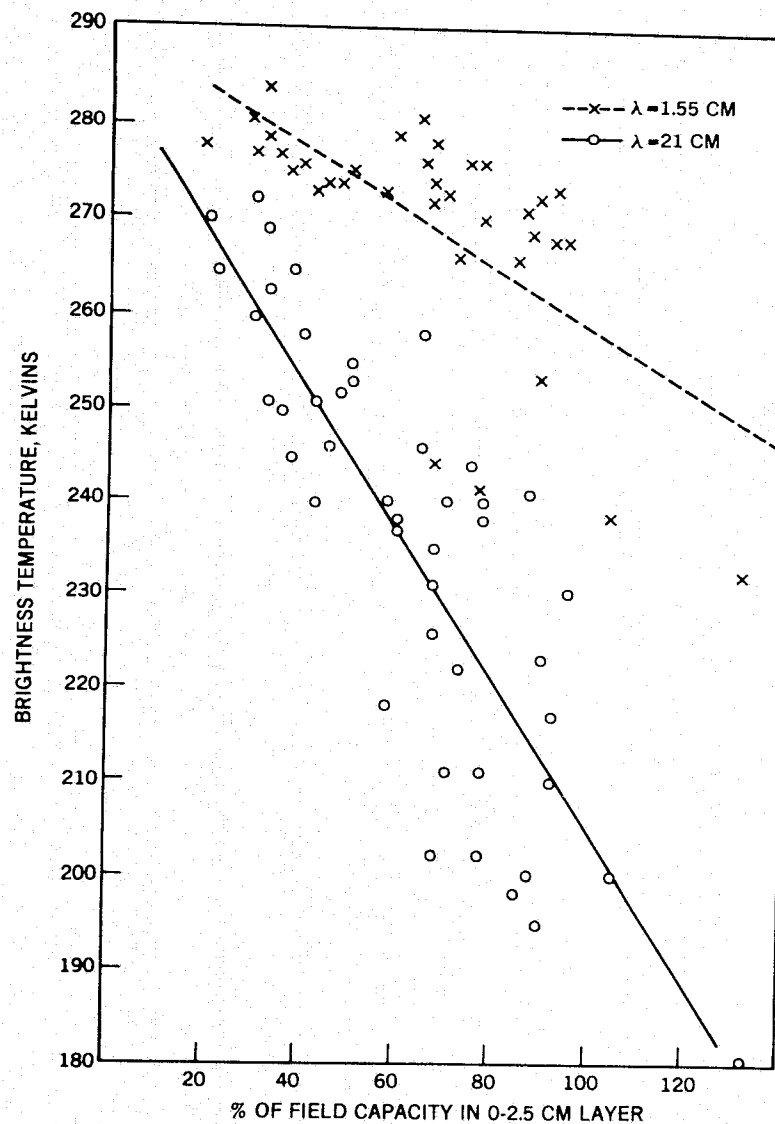


Figure 3: Brightness temperature for vegetated fields (alfalfa and wheat up to 60 cm tall) versus percent of field capacity in the 0- to 2.5-cm soil layer [20].

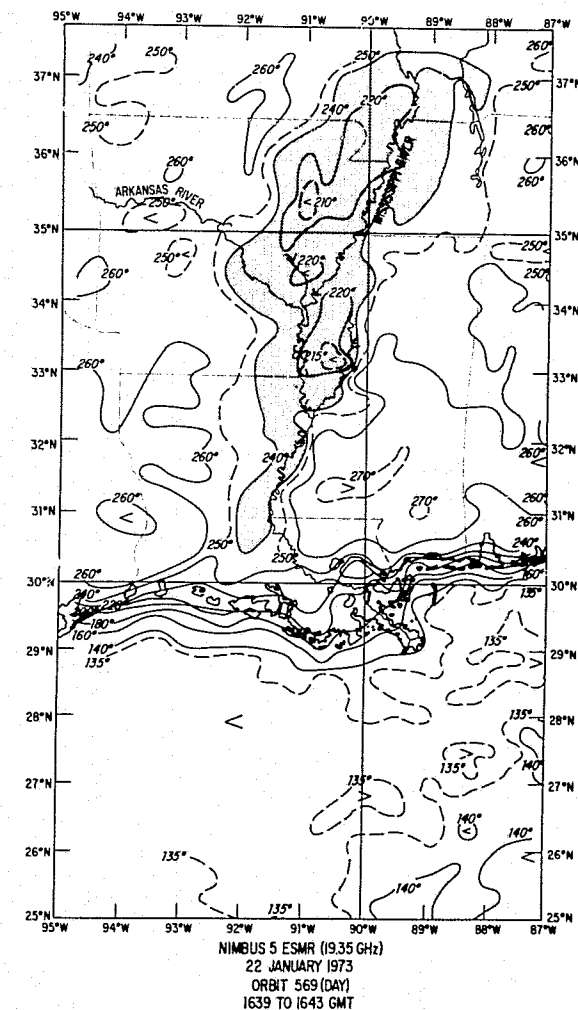


Figure 4: A brightness temperature contour map of the lower Mississippi Valley using the data of 22 January 1973. The contour interval is 10°K.

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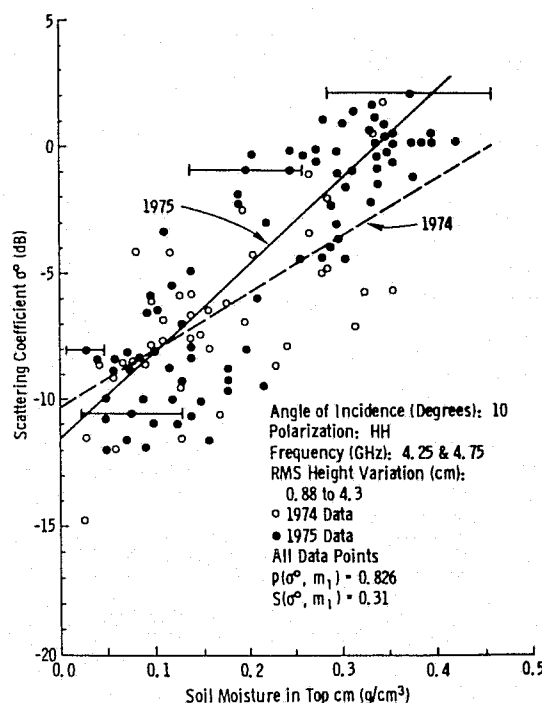


Figure 5: Backscattering coefficient as a function of moisture content, measured volumetrically in the top 1 cm of the soil, 1974 data is for soil with 49% clay while the 1975 data is for soil with only 17% clay. The horizontal bars represent one standard deviation around the mean soil moisture measured in the field.

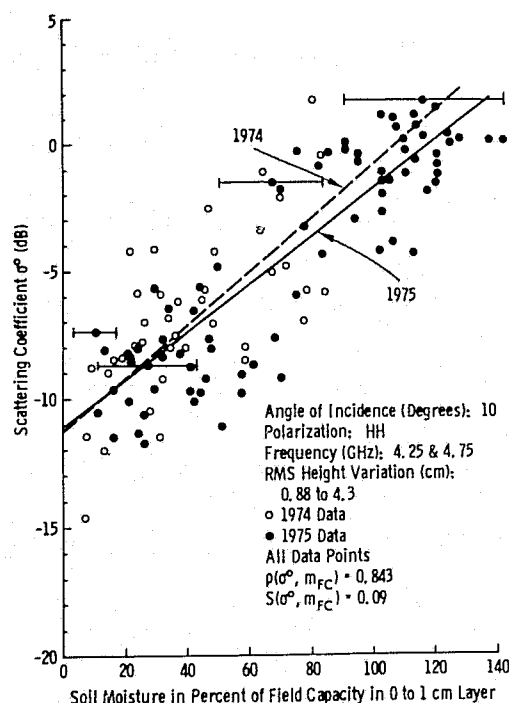


Figure 6: Same as Figure 5 except moisture is expressed as percent of field capacity

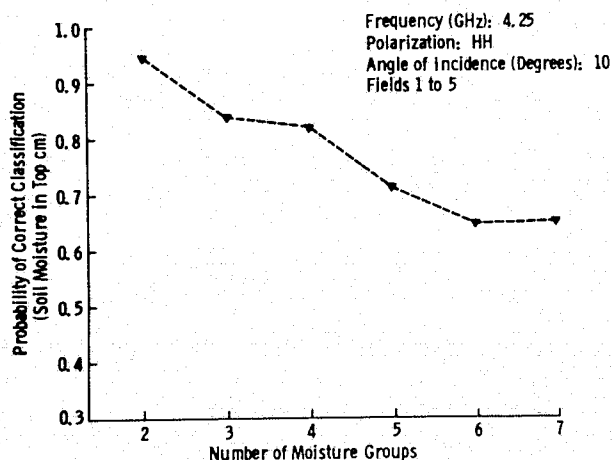


Figure 7: The probability of correctly classifying soil moisture plotted as a function of moisture groups, Battilvala and Ulaby [9]

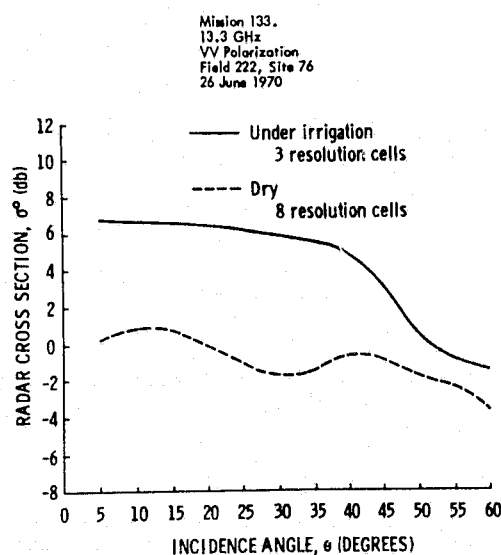


Figure 8: Scattering coefficient as a function of incidence angle for irrigated and non-irrigated sections of a corn field, Dickey, et. al. [30].

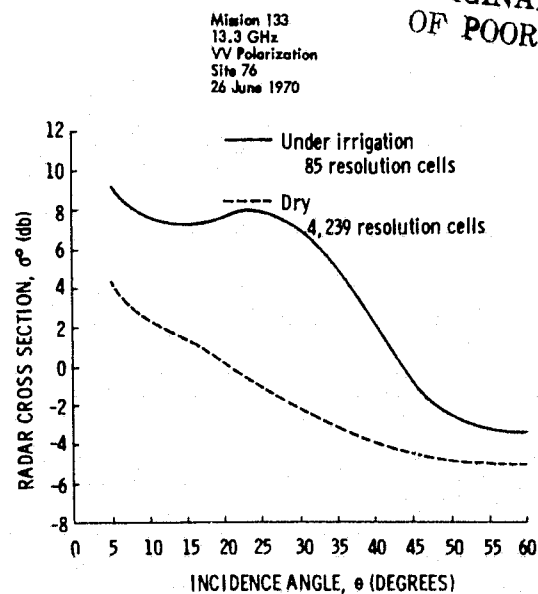


Figure 9: Average scattering coefficient as a function of incidence angle for irrigated and dry terrain, Dickey, et. al. [30].

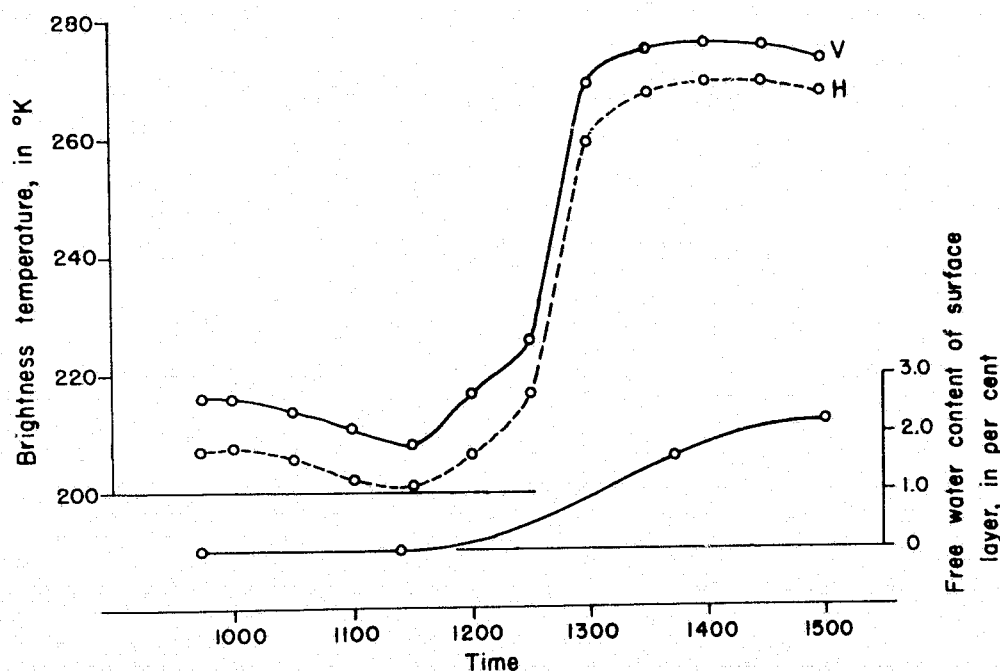


Figure 10: MEASURED CHANGE IN BRIGHTNESS TEMPERATURE WITH APPEARANCE OF LIQUID WATER. Graph shows microwave emission at 0.8 cm, 45° viewing angle for a snowpack *in situ* as a function of time. Prior to 1200 hours, the whole snowpack was cold and dry. By 1500 hours appreciable liquid water had appeared in upper layers but lower part of snowpack was relatively dry. Snow density 517 kg/m³, thickness 0.8 m. Crater Lake, Oregon, March 22, 1970, Meier and Edgerton [31].

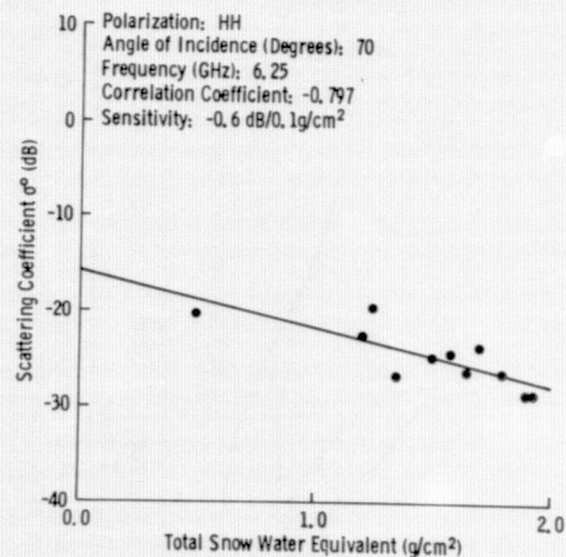


Figure 11: Response of σ^0 to Total Snow Water Content per Unit Area.

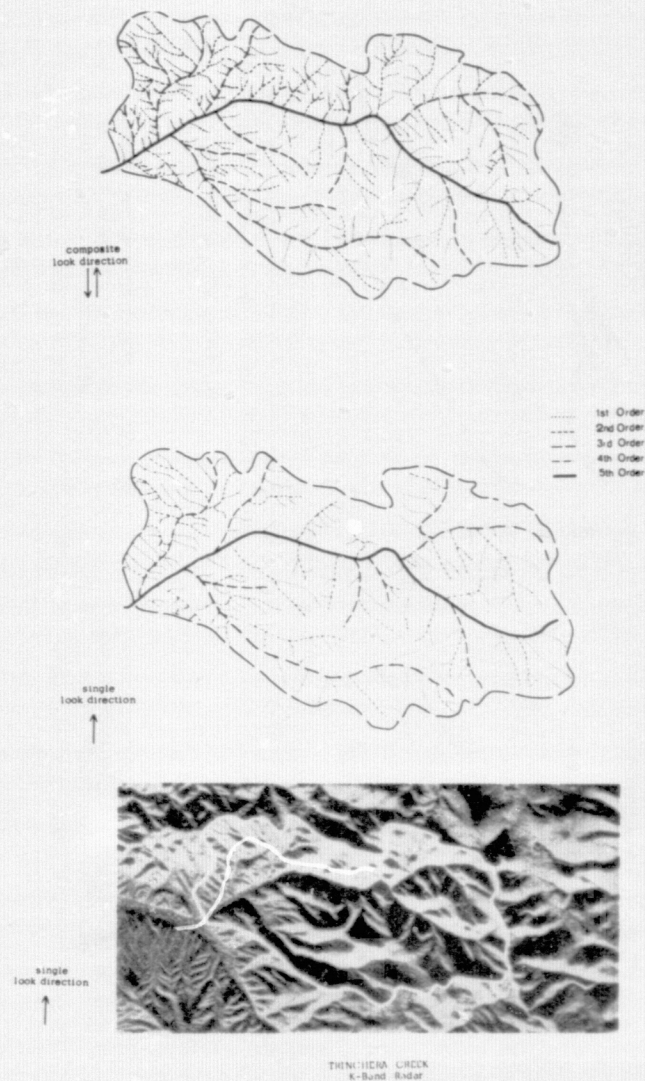


Figure 12: The utility of radar for drainage mapping is clearly illustrated by the above K-band image of Trinchera Creek, Colorado. Multiple views increases the amount of stream detail in mountainous terrain, McCoy [34].

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RADAR FLOOD MONITORING

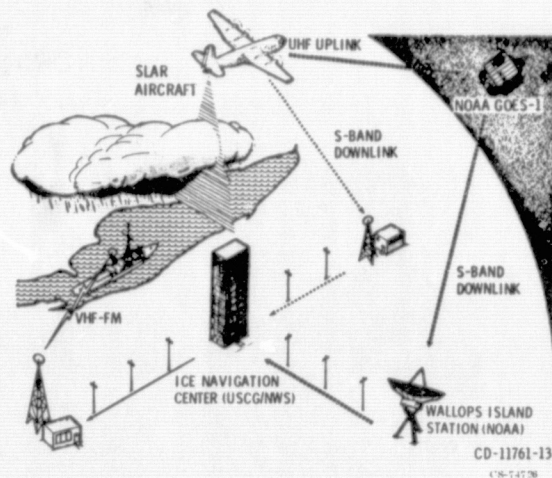
...THROUGH CLOUDS

...AT NIGHT



Figure 13: Radar Image of the 1973 Missouri River Flood near St. Louis

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Figure 14: Schematic of the Great Lakes
Microwave Ice Information Program
(Project Icewarn(), Schertler et.al. [37].

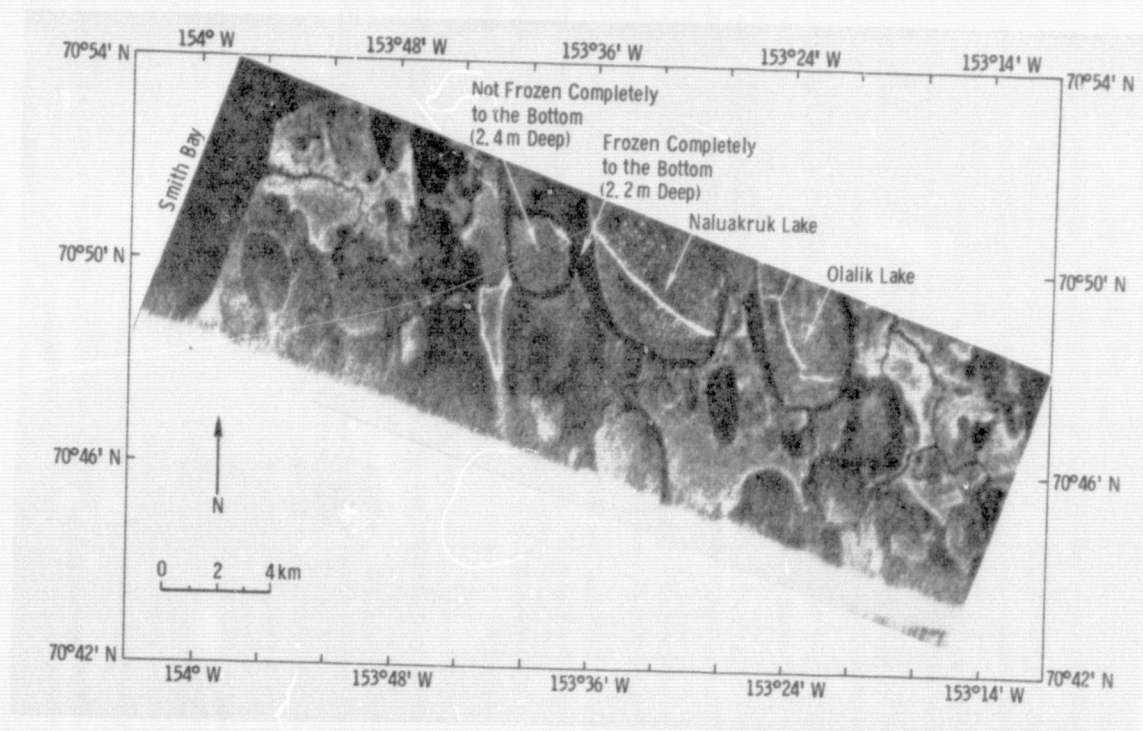


Figure 15: L-band imagery of the Naluakruk Lake near Smith Bay on
the North Slope of Alaska, Weeks, et. al. [43].

N78-14469

UTILIZATION OF REMOTE SENSING OBSERVATIONS
IN HYDROLOGIC MODELS

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INTRODUCTION

The planning, design, and management of water resource systems must reconcile a complex array of conflicting demands. Thus, decision makers working on water resource problems must use every aid available to them as they anticipate the consequences of their actions. A very important phase of the water resource decision making process involves the use of hydrologic models to simulate the streamflows or water quality parameters under different conditions. For example, as part of the process of deciding whether to install a series of small reservoirs distributed throughout the watershed as opposed to one large reservoir on the main stream, the decision makers would use a hydrologic model to examine the changes that each action would have on the frequency of flooding and the accompanying economic damages.

There is a wide range of hydrologic models available today. Many of these models are structured in such a way that remote sensing has little or no application with them. Models calibrated against historical stream flow, for example, would be in this class. However, the recent emphasis on environmental concerns and the increasing conflicts placed on the use of a limited water resource has lead to the development of a family of computer-based models that simulate the behavior of the various components of the runoff cycle. Many of these models require input parameters that center on land covers and are appropriate for interfacing with remote sensing capabilities. The advantage of a model having parameters defined in terms of land cover is that it allows experimentation with alternate forms of watershed development and the assessment of future changes that might occur. The basic approach with such a model is to calibrate it to reflect the hydrologic or water quality consequences of an existing land cover pattern. Once the decision maker is satisfied that the model adequately represents the system, he then has a tool which allows him to experiment and evaluate the impact of changes that he might be considering. Unfortunately, estimating parameters in terms of land cover when areas in excess of several square kilometers are involved is a difficult and time consuming task. Frequently, parameter estimating problems lead decision makers to adopt simpler models requiring less detailed input data or to inadequately define the data required by the model.

Experiences with the economic and time requirements of defining input data have had a major impact on recent trends in model structure. Our inability to define input data is actually taking us backwards in the state-of-the-art of the models themselves. In the 1960's and early 1970's we evolved from the very simple empirical models developed many years ago to very complex computer-based simulators. Now, we are actually going back to more simple models because of our inability to either define or manage the input data. Figure 1, shows a schematic of one of the more popular models proposed for urban studies, that developed by the Environmental Protection Agency (1971). In this model, the user simulates the behavior of the overland flow process, infiltration, flow down a gutter, and flow through a pipe from a small urban sub-watershed. Early users found that they had great difficulty defining the data required by this model. As an example of the problem, McPherson (1970) has explained that Milwaukee, Wisconsin having an area of 246 square kilometers has more than 2,200 kilometers of storm and combined sewers. With catch basins spaced approximately every 150 meters, the use of the EPA model shown in Figure 1

would require the definition of all of the flow elements for as many as 14,500 inlet watersheds. On the planning level, this simply is not a realistic task. As a result, urban water resource planners are now migrating toward models similar to the Simplified EPA Model (1976) shown schematically in Figure 2. All of the flow processes in this model have been lumped into one coefficient that simply subtracts a loss function from the rainfall input. It is believed that recent developments in remote sensing technology will allow water resource decision makers to use a model that is somewhere between these two extremes.

PARAMETER DEFINITIONS FOR HYDROLOGIC MODELS

Traditionally, many hydrologic models have been designed to use map data and published meteorological information for parameter definition. One family of models which rely heavily on map data are those based on regression analysis. Many studies have shown that the concepts of hydrology and geomorphology can be blended to develop equations for estimating the discharge associated with a recurrence interval of T years, Q_T . Typically, these studies relate measured flows from a number of watersheds in a climatic region to topographic variables, X_i , that can be readily determined. The equations are usually of the form

$$Q_T = AX_1^B X_2^C X_3^D \quad (1)$$

where A, B, C, and D are numerical constants. Some of the most commonly used variables include the drainage area, main channel length, surface storage, elevation, drainage density, vegetation, slope and soil type. Many of the equations have large standard errors and are of little practical value. Others such as those developed by Thomas and Benson (1965) to estimate mean annual flows in the Potomac River Basin give excellent results and show that regionalization studies have a high potential of value as our understanding the physical processes and our ability to measure these processes improves.

A widely used model that has an excellent potential for modification to be remote sensing compatible is that developed by the Soil Conservation Service (SCS) (1972). This model, or more accurately family of models, computes direct runoff through a set of curves that were developed from field studies that measured runoff from numerous watersheds having different land cover-soil complexes. In essence, these curves represent a runoff coefficient that is a function of the distribution of land covers and soil types. The SCS defines four soil types ranging from low to high runoff potential. The soils for an area are defined from an SCS developed county soil map while the land covers must be determined from aerial photography or ground surveys. Table 1 is an example of the land cover categories used by this model.

Another model that can be interfaced with remote sensing is STORM (Storage, Treatment, Overflow, Runoff Model) developed by the Corps of Engineers (1976). It is intended for use as a planning model in which a wide array of watershed management alternatives can be screened very rapidly. This model is a continuous streamflow generator that produces simulated hourly discharges for an entire period of record. One version of STORM is much like the SCS model while a second uses a basic runoff equation given as

$$Q = C (p-f) A \quad (2)$$

where Q is a stormwater runoff rate in inches per hour, T is the average hourly precipitation, A is the watershed area, f is the depression storage, and C is a runoff coefficient defined as

$$C = C_p (1-IMP) + C_i (IMP) \quad (3)$$

C_p is a coefficient for the pervious area, C_i is a runoff coefficient for the impervious areas and IMP is the fraction of the watershed that is impervious.

The SCS related version of STORM uses the land use designations presented in Table 1 while the other option requires the percentages of the watershed devoted to single unit residential, multi-residential, commercial, industrial, and open space. As with the SCS models, current practice has the percentages of the land covers being determined by planimetering from air photos. Representative imperviousnesses associated with each of the land covers are then determined by detailed analysis of typical areas within each category.

MODEL MODIFICATIONS FOR REMOTE SENSING CAPABILITY

Hydrologists, as with many professionals concerned with earth resources, are frequently hesitant to adopt a remote sensing tool because of its resolution, especially when Landsat is being considered. Often, this hesitancy is unjustified because of the accuracy of the model and its ability to correctly reflect the impact of variations in a particular parameter. For example, even when we correctly identify an area as being single unit residential housing, the primary parameter with which we are concerned is the percent of imperviousness of this area. Numerous studies have shown that imperviousness varies widely within a residential area even though the housing density may be relatively constant. Thus, when a hydrologist uses representative values, such as an average imperviousness for single unit residential housing, he must recognize that he cannot apply his model to extremely small areas if his results are to be meaningful. When one recognizes that parameters based on averages cannot be used on small areas the resolution of the picture element becomes less important. Salomonson, Ambaruch, Rango and Ormsby (1975) have presented an excellent discussion of the interaction between model sensitivity and parameter estimation with remote sensing.

Another factor that must be considered when deciding how to define input data to a model is the basic limitation of our knowledge of the processes we are trying to simulate. We have to ask ourselves the question that if we could develop perfect data, is our understanding of the process sufficient to give us exact results. The hydrologist who understands his model recognizes that simplifications have had to be made to the equations in order to obtain solutions within the storage and running times available on conventional computers. With such an understanding one can make informed decisions concerning the impact that different approaches to parameter definition will have on model performance.

The SCS model, whose land cover input requirements are described in Table 1, is an empirical model based on field observations from throughout the United States. As a result, the curve numbers, or runoff coefficients, are not unique values. Rather, the curve numbers represent averages that are subject to a significant standard error. Recognizing that this error existed, Ragan and Jackson (1976) reduced the land covers of Table 1 to that of Table 2 which, as many studies have shown, can be defined by computer aided classification of Landsat data.

The model STORM is especially attractive for modification to a remote sensing capability because of the limited land use requirements mentioned in the text following equation 3. Actually, the quantity component of this model does not even need land cover to make the model function. The key parameter is the percent of imperviousness which Ragan and Jackson (1976) have shown can be estimated with Landsat.

It is also possible to modify the regression type models illustrated by equation 1. In this approach, one recognizes that it may not be possible to measure watershed area from Landsat or other remote sensors. However, it is possible to measure parameters that are highly correlated with the area. For example, numerous geomorphic studies have shown that stream length and area are highly correlated within a region. Rango, Foster, and Solomonson (1975)

have shown that stream length can be measured quite accurately from Landsat in some regions. Thus, in using remote sensing one would not attempt to measure area. Rather one would measure the length of the main stream or the total length of streams and develop the regression equation with this parameter instead of area. The author believes that there is an excellent potential for a new family of regression models that will be based on remotely sensed rather than map variables.

EXPERIENCES WITH REMOTE SENSING BASED MODELS

Blanchard (1975) was one of the first hydrologists to experiment with the modification of an existing model to one that was more appropriate for remote sensing. Instead of using Table 1, Blanchard estimated runoff curve numbers for the SCS Model directly by using reflectance measurements obtained for a series of watersheds from the Landsat multispectral scanner (MSS). The satellite derived curve numbers were compared with those computed from measured runoff and those conventionally derived through the use of Table 1. Blanchard concluded that the reflectance measurements were more reliable than the Table 1 based approach because of the subjectivity of the individual making the land cover delineations and estimating the soil types.

Ragan and Jackson (1976) conducted further experiments with the SCS model in a study on a 54 square km. watershed in the suburbs of Washington, D.C. In this experiment, a local government used 1:4800 aerial photographs and detailed soil maps to define curve numbers from Table 1 which were then used to compute a synthetic flood frequency series for peak flows having recurrence intervals between two and one hundred years. A second team used NASA U-2 color infrared photography blown up to a scale of 1:24000. Land covers defined by Table 1 were interfaced with digitized soil data to obtain a curve number which was used to generate a second frequency series. A third team classified the watershed from Landsat digital tapes and a general soil map in accordance with the land covers listed in Table 2. Table 3 compares the discharges and resulting depths of streamflow obtained by the three approaches. The results of this experiment were extremely encouraging.

A much more extensive comparison between the results obtained with conventional and remote sensing based models was made by Ragan, Jackson, Fitch, and Shubinski (1976). In this study, a consulting engineering firm had been retained to conduct a watershed planning study on the highly urbanized 50 square km. Four Mile Run watershed in the Virginia suburbs of Washington, D. C. In this meeting the responsibilities to their client, the consulting firm used the best available conventional data to define parameters required by STORM which was operated to examine the impact of a number of flood control alternatives. In order to evaluate the utility of Landsat MSS data as a tool for urban water resources planning the consultant then ran STORM under the same conditions as those required to meet his obligations to his client, but with the input data based on Landsat estimated parameters. The conventional version of STORM was calibrated against both existing land cover and historical streamflow data. The Landsat based version of STORM considered the watershed to be ungauged and based the input parameters on existing land cover and streamflow records from similar watersheds in the region as described by Jackson, Ragan and Shubinski (1976). Table 4 is a comparison of STORM parameters estimated by the conventional and Landsat based techniques. Although these parameters differ slightly, the synthetic flow frequency curves and discharge hydrographs compared extremely well. Perhaps the most important element of this study is the data presented in Table 5 which shows the reduction in annual flood damages that could be expected by various flood control techniques. Both versions of the model show very little to be gained by on-site detention storage in this particular watershed while a major gain was obtained by channelization and removing obstructions in the existing stream network. The conclusion was that if the modeling process had been conducted using Landsat based rather than

conventionally defined parameters in STORM, the decisions concerning which control alternatives to adopt would have been the same.

Algazi and Suk (1977) are continuing to experiment with the use of Landsat data to define parameters in the hydrologic model STORM. Their current experiments are being conducted on the Trail Creek Watershed near Atlanta, Georgia and the Castro Valley Watershed in California. In addition to the modeling Algazi and Suk are experimenting with new pattern recognition techniques that show considerable promise as practical tools for hydrologists using Landsat as tool.

An important need for the initial phases of water resource investigations is a remote sensing based model that can estimate monthly flows from watershed characteristics and precipitation data. Holtan, Ormsby, and Fisher (1977) used Landsat to define the land cover required for a model that is an outgrowth of the SCS models. They also used low altitude aerial photography to estimate land cover changes during the period 1963 - 1974. As shown by Figure 3, the results of this experiment are quite encouraging. The curves labeled A that used the actual land use for each year, as obtained from the aerial photography, indicates that the model is satisfactorily reproducing the behavior of the watershed. Curve B illustrates how the monthly discharges would have been under-estimated if only the 1963 data had been used while Curve C shows the behavior of the watershed if current land use had been present for the period of record.

A major component in models used to synthesize monthly flows is an estimate of the evaporation and transpiration (E-T) taking place in the watershed. Khorram (1977) has been experimenting with a remote sensing based information system for estimating E-T for a series of watersheds in California. One phase of this experiment centers the estimates on Landsat and NOAA satellite data while other phases use aerial photography. The experiment is still in progress, but the initial results indicate that this approach has a high potential for success.

A major attraction of remote sensing based hydrologic models, especially those using digital information such as Landsat, is the ability to work from a large area data base. When taking advantage of this approach, an entire area of jurisdiction is classified and then information on individual watersheds is extracted as needed from the overall data base. Schecter (1976) has described the use of Landsat to develop ten land cover categories for the 1750 square mile Triangle J Council of Governments in North Carolina. In that approach, the Council stores the Landsat defined land covers on its own computers and then interfaces this data with digital files containing soil, slope, and rainfall to estimate the areal distribution of the quantity and quality of runoff using the EPA Storm Water Management Model. There are a number of other jurisdictions that are currently involved in similar tasks.

In many areas of the world, such as the Western United States, a large portion of the available water comes as runoff from the snow pack. Rango, Solomonson, and Foster (1977) and Rango and Itten (1976) describe regression models that have been developed for several areas that relate area of snow cover to seasonal streamflow. The paper by Rango that appears elsewhere in these proceedings provides additional information on these experiments.

A recently evolved concept in hydrology hypothesizes that only a small portion of the watershed actually produces runoff during periods of rainfall. This is a major departure from the traditional concepts that have overland flow taking place across all areas of the watershed and moving toward the stream network after the infiltration capacity of the soil has been satisfied. Ishaq (1974) conducted field studies on a series of watersheds to examine the mechanisms associated with such a concept. Ishaq used densitometric analysis of aircraft color infrared imagery to show a correlation between transmittance

and zones of high moisture content which he was able to define as being "the hydrologically active" portions of the basin. Figure 4 shows the "hydrologically active" areas of one of his watersheds that were delineated with the remote sensing technique. The relatively small portion contributing runoff in this watershed is very striking and consistent with the theoretical and experimental findings obtained by other investigators using different techniques.

TIME AND COST COMPARISONS

The economics and manpower requirements associated with the use of conventional and various remote sensing techniques in hydrologic modeling is quite limited. The Four Mile Run Study of Ragan et al (1976) required 110 man days at a cost of \$14,000 to develop the parameters for STORM using 1:3600 color aerial photographs. Development of STORM inputs using computer aided classification of Landsat digital data and limited photographic sampling required 6.9 man days at a cost of approximately \$2350. When large areas involving numerous watersheds are involved, the economic attractiveness of Landsat becomes dramatic. The land cover data base reported by Schecter (1976) was developed for approximately \$4.00 per square mile.

Experiences with the Four Mile Run Study, experiments with the SCS Model, and discussions with other investigators indicate that savings of 50 to 75 percent can be achieved with well designed remote sensing approaches. The decision on sensor use is heavily dependent on the operations of the organization involved and the value of the results. An organization that has access to a large number of non-paid college interns can afford to use 1:4900 aerial photographs. Another organization that must account for technical manpower at \$12.50 per hour (including overhead, etc.) may quickly decide to turn to Landsat or U-2 photography.

We must also spend more time on the development of techniques that will allow us to make informed estimates of the price that we should be willing to pay for remote sensing based on the use we will get from it. An example of such an effort was included as part of the Four Mile Run Study as Jackson and Ragan (1975) used Bayesian Decision Theory to estimate the inter-relationships among sensor accuracy, product price, and the economic consequences of errors on the watershed management decisions. There are too many instances of input data to a model either being over or under defined.

FUTURE DIRECTIONS

A major need in hydrologic modeling, especially those models supporting operational decisions, is the capability to estimate soil moisture. The work Schmugge (1974) and Idso, Jackson, and Reginado (1975) indicates that thermal inertial and microwave techniques will someday meet this very important requirement. This will be a major step beyond our current approaches that estimate changes in soil moisture from an ill-defined initial condition based on meteorological data.

The better models have parameters that are based on the hydrologic responsiveness of the soils. We can anticipate improvements in our ability to make hydrologic soil classifications with remote sensing technology. Wong, Thornburn and Khoury (1977) have been experimenting with the merging of remote sensing and digital terrain data to identify soils within a region of similar climatic and geologic characteristics. It is widely recognized that soil types are reflected by vegetative cover characteristics, surface geometry and drainage characteristics. The blending of remote sensing and terrain data offer great promise as an automatic technique of soil classification at least to the level required for hydrologic work. Landgrebe and his co-workers (1974) had successful results in the use of Landsat to identify general soil types in parts of Indiana and Kansas. Also, Hitchcock, Cox, Baxter and

Smarm (1975) have shown that Landsat derived land cover and soil data can be successfully overlaid by digital techniques to improve our understanding of the inter-relationship of these parameters. A number of other experimentors have shown similar capabilities for interfacing data of different sources.

Because no single remote sensor will ever satisfy all the needs of hydrologic modeling, the ability to efficiently interface data from a number of sources is paramount to this success in the endeavor. Considerable progress has been made in this area and it can be anticipated that significant new break throughs will be occurring because of the intensity of the effort being applied to the interfacing problem.

Remote sensing may lead us to a new definition of a sub-watershed type. Instead of trying to manage data on sub-watersheds based on their true geographical boundaries, perhaps our simulation will be done through the linkage of a series of rectangular cells distributed throughout the watershed. Salmon, Denouvillie, Chart, Wolley and Cadou (1963) developed the concept storing watershed data in a square grid system for computer simulation of the runoff processes. Their work has not received wide attention in the hydrologic community, but with a move into remote sensing their approach could achieve new importance.

CONCLUSION

Most of the remote sensing related work in hydrologic modeling has centered on modifying existing models to take advantage of the capabilities of new sensor techniques. There have been enough success with this approach to insure that remote sensing is a powerful tool in modeling the watershed processes. Unfortunately, many of the models in use were designed without recognizing the growth of remote sensing technology. Thus, their parameters were selected to be map or field crew definable. It is believed that the real benefits will come through the evolution of new models having new parameters that are developed specifically to take advantage of our capabilities in remote sensing. The ability to define hydrologically active areas could have a significant impact. The ability to define soil moisture and the evolution of new techniques to estimate evapotranspiration could significantly modify our approach to hydrologic modeling. Still, without a major educational effort to develop an understanding of the techniques used to extract parameter estimates from remote sensing data, the potential offered by this new technology will not be achieved.

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Table 1
Runoff Curve Numbers for SCS Model
(from SCS (1975))

LAND USE DESCRIPTION	HYDROLOGIC SOIL GROUP			
	A	B	C	D
Cultivated land ^{1/} : without conservation treatment	72	81	88	91
: with conservation treatment	62	71	78	81
Pasture or range land: poor condition	68	79	86	89
good condition	39	61	74	80
Meadow: good condition	30	58	71	78
Wood or Forest land: thin stand, poor cover, no mulch	45	66	77	83
good cover ^{1/}	25	55	70	77
Open Spaces, lawns, parks, golf courses, cemeteries, etc. good condition: grass cover on 75% or more of the area fair condition: grass cover on 50% to 75% of the area	39 49	61 69	74 79	80 84
Commercial and business areas (85% impervious)	89	92	94	95
Industrial districts (72% impervious).	81	88	91	93
Residential: ^{1/}				
Average lot size Average % Impervious ^{1/}				
1/8 acre or less 65	77	85	90	92
1/4 acre 38	61	75	83	87
1/3 acre 30	57	72	81	86
1/2 acre 25	54	70	80	85
1 acre 20	51	68	79	84
Paved parking lots, roofs, driveways, etc. ^{1/}	98	98	98	98
Streets and roads:				
paved with curbs and storm sewers ^{1/}	98	98	98	98
gravel	76	85	89	91
dirt	72	82	87	89

TABLE 2
Runoff Curve Numbers for Land Cover Delineations
Definable from Landsat.

Land Use Description	Hydrologic A	Soil B	Group C	Group D
Forest Land	25	55	70	77
Grassed Open Space	36	60	73	78
Highly Imperviousness (Commercial, Industrial, Large Parking Lot)*	90	93	94	95
Residential	60	74	83	87
Bare Ground	72	82	88	90

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TABLE 3
Discharges and River Stages Computed with SCS Models
Randolph Road Gaging Station on Northwest Branch of Anacostia River

Return Period (yrs)	Precip. (in)	Discharge (cfs)			Depth of Flow (ft)		
		TR-20	LANDSAT	U-2	TR-20	LANDSAT	U-2
2	3.0	2990	3490	3850	8.9	9.3	9.6
5	3.3	4610	5140	6064	10.0	10.4	10.9
10	5.4	6210	6900	7580	10.9	11.3	11.7
25	5.8	7390	8759	9300	11.7	12.3	12.7
50	6.7	9020	9900	10400	12.5	13.0	13.3
100	7.3	10,780	11,100	11,806	13.5	13.6	14.1

TABLE 4
Parameters Used in Conventional
and Landsat Versions of STORM

Parameter	Conventional Version	LANDSAT Version
Watershed Imperviousness (%)	34.6	39.1
C_p	.39	.32
C_I	.90	.86
C	.57	.53
f_{max} (inches)	.25	.18

TABLE 5
IMPACT ASSESSMENT OF FLOOD CONTROL ALTERNATIVES
USING CONVENTIONAL AND LANDSAT-BASED STORM MODELS

ACTION		PERCENT REDUCTION IN ANNUAL DAMAGES	
		CONVENTIONAL STORM	LANDSAT-BASED STORM
Detention Storage (equivalent inches over the watershed)	0.10	3.7	4.8
	0.20	7.5	8.5
	0.30	10.6	11.8
Channelization, widen bridge open- ings, and remove culvert at rail- road yard (USACE Project)		97.7	97.6

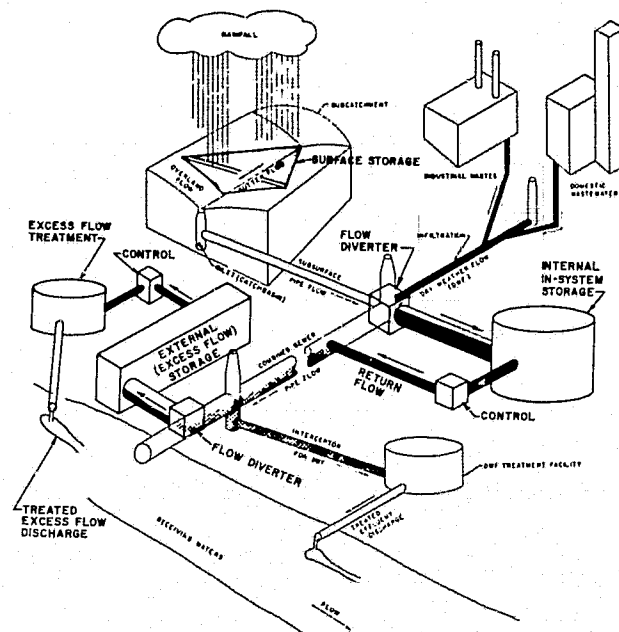


FIGURE 1
Schematic of EPA Stormwater Management Model
(from EPA (1971))

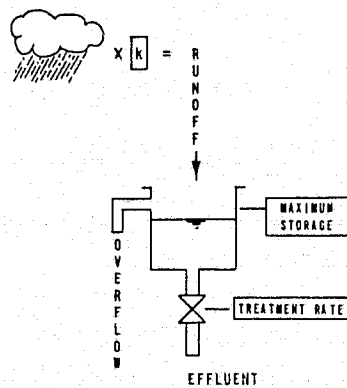


FIGURE 2
Schematic of "Simplified EPA Model"
(from EPA (1976))

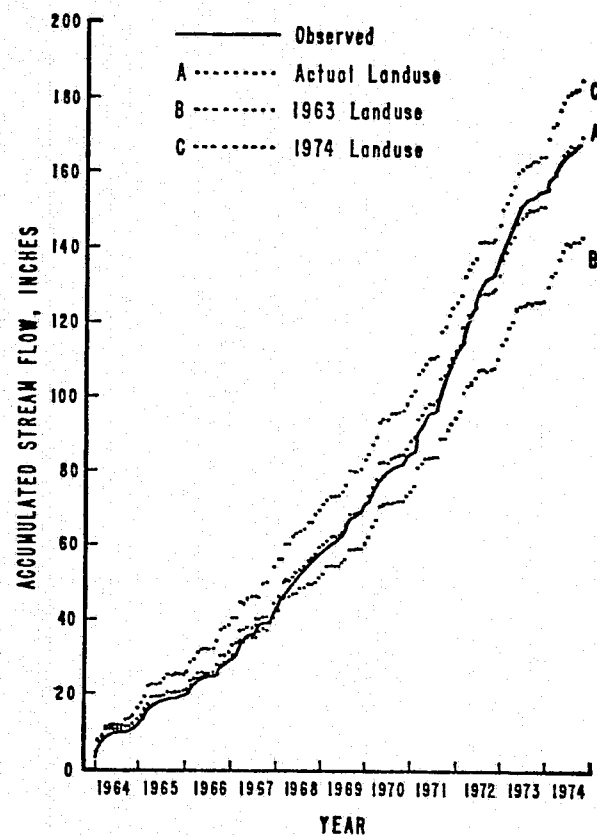


FIGURE 3

Comparison of Computed Streamflow with Observed Streamflow on Western Branch of the Patuxent River, Maryland

(from Holton et al (1977))

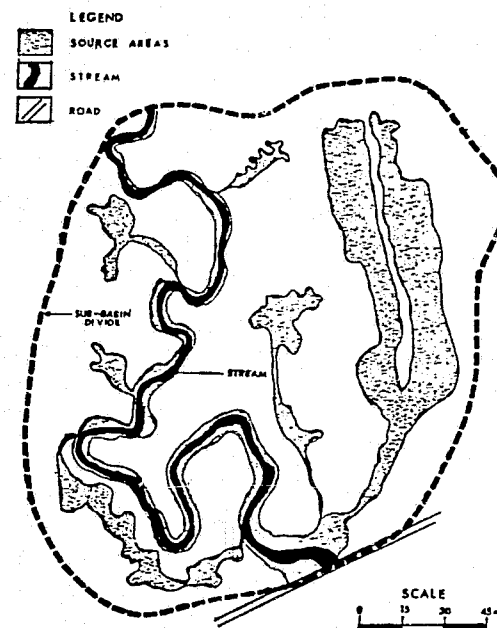


FIGURE 4

Hydrologically Active Areas of Lowery Creek Watershed (from Ishaq (1974))

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THE IMPACT OF REMOTE SENSING ON UNITED STATES' GEOGRAPHY
THE PAST IN PERSPECTIVE, PRESENT REALITIES, FUTURE POTENTIALS

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INTRODUCTION

This paper examines some impacts of remote sensing - still a relatively new technology - on geography, a discipline which traces its origins back to the beginning of learning. As geographers deeply involved in this new technology, and with a vision of its future value to our discipline, we are concerned at the modest impacts of remote sensing on some major research areas in geography. Even acknowledging that in a broader view of things, its impact on geography has been as great or greater than in other disciplines, does not alleviate our concerns over the following: 1) few senior academics in geography have research underway in remote sensing, 2) economic geographers, who constitute a sizable body of geographically trained professionals, have virtually nothing to do with remote sensing, 3) even fewer regional geographers - notable among them those with interests in the less developed countries - have remote sensing as a research professional interest, and 4) although there has been a growth in the number of remote sensing related courses offered by departments of geography this has not been accompanied by an increase in research publication in major geographic journals.

In the following pages we examine these concerns along with some encouraging signs such as the relative strength of remote sensing among physical geographers and especially among cartographers. To set the stage for these discussions we first give a brief history of remote sensing within geography. The current status of remote sensing within the profession is then examined for academics and to a lesser degree the government and private sectors. The paper concludes with an extended discussion of the ability of remotely sensed data to provide information within the context of the explanatory forms (Harvey, 1969) employed by geographers. This is accomplished within the framework of the questions: 1) What does remote sensing permit the geographer to do now better than he has been able to do in the past? 2) What does remote sensing permit the geographer to do now that he may have been unable to do in the past? and; 3) What may remote sensing enable us to do in the future which could be of significance to the academic and professional geographers?

THE PAST IN PERSPECTIVE

Kirk Stone in his chapter "Developing Geographical Remote Sensing" in Estes and Senger's book Remote Sensing Techniques for Environmental Analysis, identifies the following five phases in the development of geographical remote sensing (Stone, 1974):

- slow recognition that the first photographs taken from the air had utility for mapping;
- a brief period of experimental use of air photos for mapping various physical and cultural landscape elements coupled with rapid wartime development of air photo interpretation as a sophisticated intelligence-gathering technique;

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- the extension of peacetime uses;
- a fourth phase with primary emphasis on the applied use of air photo interpretation in geography;
- more recently, the adjustment of these applications to the expansion of data gathering and analysis into nonvisible regions of the electromagnetic spectrum (EMR).

Although aerial photography had been available for some 40 years, it was around the beginning of the century that geographers in the United States began to realize the potential of air photos as an aid to geographic research. During World War I, those in military units began to see significant peacetime uses for the early military coverage. The first major geographic publication on the subject was the American Geographical Society's Special Publication No. 4, The Face of the Earth as Seen from the Air, by Willis T. Lee, published in 1922. This book introduced American geographers to the concept of viewing "familiar scenes from a new angle," i.e. the aerial perspective. Other pioneering works of the period include Joerg's "The Use of Airplane Photography in City Geography" (1923) and Johnson and Platt's Peru from the Air (1930). In the 1920's aerial photography in the United States was acquired for topographic mapping purposes. This quickly became the dominant use of air photos. Interpreters working with these photos stressed the cartographic aspects of the coverage. This effort led to the long-term program of photographing the entire United States at regular intervals beginning about 1930.

1920-1950

The plan to photograph the whole nation originally had two primary objectives. One was the medium-scale topographic mapping of the whole nation. The other was large-scale localized mapping for official payments based on the acreages of individual fields to farmers participating in crop payment programs. During this period American geographers experimented with this photography with regard to both systematic topics and areal differentiation. Geographers began to take photos to the field trying to determine causes of observable differences in texture and tone. An article by Russell, Forester and McMurtry (1943) is considered a classic example of utilizing aerial photography for an overall inventory. The use of air photos also continued in small-scale geographic studies (Rich, 1942; Light, 1944). In addition, an article by Stone (1948) on Alaskan vegetation keys illustrated the interpretation of small-scale coverage (1:35,000 to 1:50,000) for land classification.

As the Department of Agriculture obtained additional coverage, few geographers experimented with them. Roscoe (1960) attributed this early reluctance to:

- the lack of geographic training in interpretation techniques and the relative difficulty of acquiring coverage;
- the multiple objectives of geographic investigations and the fact that some geographers might avoid the use of aerial photos because they could not identify all images contained therein; and
- last and potentially most important, the lack of commercial demand for the geographer's interpreted product.

It is probable, however, that some of the lack of application probably reflected changes in the basic objectives of American geography; strong physical emphases were weakening in favor of more culturally oriented man-land focuses (Stone, 1974). During this period, European geographers were also putting air photos to use. The status of air photo interpretation and aerial photos in ecologic research by Troll (1939 and 1943) and air photo and geomorphologic research by Bobek (1941) are important contributions to the literature.

During World War II, air photo interpretation came into its own as an in-

telligence gathering technique. Geographers, both foreign and domestic, were trained as photo interpreters. Interpretation was accomplished at two levels, tactical and strategic. Emphasis was given to the preparation and use of "keys" by which identifications of items with immediate military significance could be made rapidly regardless of an interpreter's previous experience. This wartime exposure provided excellent training leading many qualified geographers to peacetime applications and instruction. At the end of the period, the principal geographical articles published in the United States were still largely general and descriptive (Carls, 1947; Lang, 1947; Stokes, 1950; Foster, 1951; Kohn, 1951; Kesseli, 1952; MacFadden, 1952).

1945-1960

The period between 1945 and 1960 saw the expansion of aerial photographic interpretation in geography college curricula and a rapid diversification of techniques and instrumentation employed in the field. By 1950, some 13 geography departments all east of the Mississippi River offered courses in aerial photographic interpretation (see Figure 1). The main concentration of these schools was in the Northeastern United States, from Illinois and Wisconsin in the West to Massachusetts in the East. A small discontinuous concentration existed in the Deep South with courses taught in Louisiana, Alabama and Georgia (Schwendeman, 1951).

By 1960, the number of institutions offering courses in aerial photographic interpretation had grown to 25 (see Figure 2). The pattern in 1960-61 indicates definite geographical shifts with schools on the Pacific Coast as well as in Colorado and Utah offering courses in air photo interpretation, with some original institutions in the Northeast no longer represented (Schwendeman, 1961). In 1960, of the 25 institutions teaching photographic interpretation, 20 offered graduate degree programs in geography (see Table 1). During this period geographers were still working on the development of interpretation keys for physical and cultural elements of the landscape (Black, 1955; Lewis, 1957; Kedar, 1959). Some investigations of the potential of automated image analysis was also initiated (Latham, 1959). In general, it is safe to say that most work of the period was overly optimistic in spite of occasional warnings (Stone, 1974). Also, geographical writings on problems employing air photo interpretation techniques during this time were still primarily descriptive and lacked thorough penetrating analysis (Stone, 1954; Stone, 1956; Kline, 1954).

1955-1962

During this period emphasis began to be placed on the analysis and significance of the data rather than on technique. This is documented by bibliographies compiled shortly after the end of this period (Honea, 1967; Honea and Prentice, 1968; and Honea and Prentice, 1970). Early applications were related to specific urban problems, such as analyses of distributions of neighborhoods with different levels of economic status, traffic direction and volume, industrial-plant classification, mapping of various land use zones, developmental planning, and the extension of census data using aerial photos (Green, 1956; Green, 1957; Green and Monier, 1959).

Similar progress was made in the interpretation of landforms and rural cultural features (Powers and Kohn, 1959). Agricultural applications were also examined through the use of air photos for the identification of crops through various growth stages as an element of land use analyses (Brunschweiler, 1957; Goodman, 1959; Karan, 1960). On the physical side, the interpretation of vegetation was also examined in some detail (Finely, 1960).

It is important to note that many uses of aerial photography were buried in the content of the particular geographical work accomplished during this time. Only occasionally did footnotes disclose the dependence of research on aerial photography as a primary data source. To a very real extent, foreign geographical research followed the same pattern.

1962-1977

Academic: In the early 1960's, coincident with the introduction of the term "remote sensing" and an increased interest within the federal government in the field, the expansion of course offerings in geography accelerated. By 1971-72 (based on information from Schwendeman, Sr. and Schwendeman, Jr., 1972; and Eitel, 1972, and response to questionnaires distributed to geography departments throughout the nation), Estes and Thaman (1974) found that 99 institutions in 37 states and the District of Columbia offered courses in either remote sensing or aerial photographic interpretation (see Figure 3, Table 1). The pattern expressed by the 1971-72 distribution is one of intrastate expansion and filling in between the three nodal areas seen in the 1960-61 distribution (see Figure 2). Of the 99 institutions in 37 states, some 74 institutions in 35 states offered graduate programs in geography (see Table 1). Thus, in a little more than a decade, there was an increase of almost 300 percent in institutions offering courses and a gain of slightly over 100 percent in the number of states where these courses were offered. Furthermore, there was also a 300 percent gain in offerings at schools with graduate programs, along with a 120 percent gain in states with graduate programs (Table 1).

In 1975-76, the total number of departments offering courses in remote sensing and/or photo interpretation was 165 (Table 1). These 165 departments are in 44 of the 50 states (Figure 4) (Schwendeman, Sr. and Schwendeman, Jr., 1976). The only states where, to the best of our knowledge, departments of geography do not currently offer either remote sensing or photo interpretation are Alaska, Arkansas, Maine, Missouri, Rhode Island and West Virginia. Thus, since 1971-72 there has been a continuous expansion in the number of institutions offering remote sensing/air photo interpretation (a 40% increase over the 1971-72 figures). A recent article by Neely (1977), lists 103 total courses taught in geography departments in remote sensing and related topics. This total represents 22% of the nationwide total of 470 courses identified in his survey. Even if we accept the degree of inconsistency between Neely's and our data to be equal in all disciplines (Neely's 103 courses to our 165), geography's role in remote sensing instruction is still significant. Geography, percent-wise, teaches more remote sensing courses than any other discipline in the country.

Publications: A factor which has contributed to the growth of interest in remote sensing in the United States is the increasing number of remote sensing symposia, the most notable symposia being the series conducted by the Environmental Research Institute of Michigan at the University of Michigan. These symposia initially resulted from recommendations of a study by a subcommittee of the National Academy of Sciences-National Research Council and the Geography Branch of the Office of Naval Research (Institute of Science and Technology, 1963). The subcommittee met in January, 1961, to discuss the need for more advanced and efficient data acquisition techniques in the earth sciences. The symposia were initiated to provide a periodic forum for assessing developments in the field of remote sensing. At the first symposium held in February, 1962, there were 72 participants including 5 geographers, whereas at the Seventh Symposium, held in May, 1971, there were 850 participants, including 46 geographers, essentially the same proportion (Figure 5). At the Tenth Symposium there were only 16 geographers out of 645 attendees.

One paper (of 15) was presented by a geographer in 1962, 12 (of 173) in 1971, 12 (of 132) in 1973, 9 (of 155) in 1974, 5 (of 146) in 1975, and 9 in 1977. Whether the decline is real and reflects a disinterest among geographers in publication in the Symposia, or a significant actual decline in remote sensing research by geographers, or whether it is an artifact, we do not know. Could it be that interest in the profession may have peaked and is now actually in decline? Possible alternative explanations include the large number of other symposia on remote sensing which do draw geographers away. Also, there has been a major cut in funding to attend the increasing number of meetings now being held which makes the choice of which meeting to attend difficult. In addition, the Remote Sensing of Environment Symposia is held every other year at a time near or coincident with the annual meeting of the Association of American Geographers.

While attendance and presentation of papers at professional meetings is an indication of interest in remote sensing among United States geographers, this interest is not yet manifest in terms of reviewed articles in geographic journals or doctoral dissertations. Few articles dealing with remote sensing related topics have appeared in professional geographic journals. The authors are not sure how to interpret this. It may arise partly because of the traditional nature of the articles accepted by these journals. The editors have consciously refused technical articles on remote sensing stating in fact that they are too technical for their journals. With respect to the latter point, a distinguished geographer and former editor of the Annals of the Association of American Geographers, John Fraser Hart, once told one of the authors in a conversation at the national meetings of the Association of American Geographers in San Francisco in 1970 that geography does not need courses in photo interpretation since any geographer "worth his salt" could interpret a photo. To some extent this statement may reflect part of the problem, not only for geographers but other disciplines as well. Whatever the reason, there is strong evidence that geographers with papers to submit, publish them elsewhere. For example, between 1960 and 1976 only 7 articles dealing with air photo/remote sensing appeared in the Annals of the Association of American Geographers, and 3 in the Geographical Review, whereas 12 appeared in the journal Remote Sensing of Environment and 42 in Photogrammetric Engineering and Remote Sensing. The interdisciplinary journal Remote Sensing of Environment was initiated through contacts with American Elsevier and a staff member of the National Academy of Sciences, a geographer, Edward Risley, in 1960. Remote Sensing of Environment is presently edited by G. J. Zissis of the University of Michigan and has served in a modest way as an outlet for geographers. Photogrammetric Engineering and Remote Sensing, the journal of the American Society of Photogrammetry, is probably the most significant outlet for remote sensing articles written by geographers. It is interesting to note that one important way in which geographers have significantly impacted remote sensing is in the area of the publication of texts and reference works. The works of Holz, 1973; Estes and Senger, 1974; Rudd, 1974; Lintz and Simonett, 1976, and soon to be published volumes edited by Richason and personnel of the Center for Urban Policy Research, as well as the text by Estes and Jensen are evidence of the commitment on the part of geographers to upgrading the quality of our information and instruction in remote sensing. The Manual of Remote Sensing published in 1975 gives additional evidence of this. Yet how does one really interpret the fact that 2 of the 8 volume editors, 7 of the 51 chapter editors and 35 of the 236 contributors to the Manual of Remote Sensing (American Society of Photogrammetry) were geographers? On the face of it, these figures appear encouraging. Upon closer scrutiny, however, we are not sure this constitutes research excellence on the part of geographers, a lack of research in significant areas by professionals in other disciplines or the existence of a geographers "good old boys" network in operation.

Research Funding: Teaching and publication in remote sensing by geographers may be, but are not necessarily associated with advanced research. Research on remote sensing topics can be a very expensive undertaking. It is not surprising, therefore, that almost all of the major academic research in geography dealing with remote sensing is funded by agencies of the Federal government. It has been this federal support which has influenced and created the environment for growth in the field of remote sensing in all disciplines from the 1960's to the present.

Funding comes mainly from the National Aeronautics and Space Administration (NASA), either directly from NASA Headquarters or through other federal sources such as the Geographic Applications Program (GAP) of the United States Geological Survey (USGS). In addition, various NASA centers (e.g. Goddard Space Flight Center, Maryland; Johnson Spacecraft Center, Houston; and Ames Research Center, Moffett Field, California) also provide research funds either directly or through various user agencies or groups. Other agencies of the Federal government who now or have provided funds for geographic research in remote sensing include the Department of Defense, through the Department of Naval Research Geography Program; ARPA; US Airforce Radar; the United States Army Engineering Topographic Laboratories, Geographic Branch; the United States

Department of Agriculture; the Department of Housing and Urban Development; and the Department of Transportation, through the United States Coast Guard.

In May, 1967, the Association of American Geographers gave evidence of the increasing interest in remote sensing as a research tool in geography by forming a Commission on the Geographic Applications of Remote Sensing under the direction of James Anderson with Robert Peplies as Executive Director. An AAG committee on Remote Sensing of Environment was also formed. The Commission has since ceased to function while the Committee has continued to promote educational programs in remote sensing within the discipline. The educational task of the Commission has been carried out through institutes, summer short courses, and workshops. Five summer short courses sponsored by the National Science Foundation and the Remote Sensing Committee of the AAG to acquaint college level teachers with this new remote sensing technology have been held. In addition, the Remote Sensing Committee has also sponsored remote sensing workshops conducted in connection with the AAG's and National Council for Geographic Education (NCGE) national meetings. Attendance at these workshops has been excellent and may well be a major factor in stimulating the growth of teaching in remote sensing in geography. Similar short courses were sponsored by the National Science Foundation during the late 60's and early 1970's.

Another significant activity of the Remote Sensing Committee of the AAG is the publication of the newsletter RSEMS - Remote Sensing of the Electromagnetic Spectrum - which began in 1974 as a quarterly with a subscription fee of \$1.00 per year. The first issues could be characterized by the whimsical motto internally proposed for adaption as a RSEMS logo "Quidnam, O Cato, Sestertio Nummo expectasses" (what did you expect for 25¢). As RSEMS has continued it has progressed into a substantive quarterly with over 1000 subscribers. The editorial staff and series of guest editors have combined to produce significant issues, classroom materials, and laboratory exercises. RSEMS is filling a need within the discipline and its improvement parallels the increasing awareness of geographers to the potential of this tool. The authors believe that it is a significant mark of the impact of remote sensing on the discipline that four sessions at the AAG National Meetings held in Salt Lake City in 1977 dealt with remote sensing and that papers in a number of other sessions used remote sensing as a primary data acquisition tool.

Private Industry and Federal, State, and Local Government Activities: Within the context of the present, two rapidly advancing areas of research and/or employment of individuals with a background in geographic remote sensing should be mentioned. These are 1) private industry; and, 2) state and local governments. The 1967 directory of the Association of American Geographers lists 7 geographers in government jobs and 3 in private industry with a speciality in remote sensing. By 1974, the year of the latest AAG directory these numbers had climbed to 43 for government and 36 for private industry, increases of 600% and 1200% respectively. There is every reason to believe that this rate of increase is continuing and may be accelerating somewhat. A complete listing of the industries and government agencies where professional geographers with remote sensing interests are employed is beyond the scope of this paper, however, companies range from Lockheed Electronics, Rockwell International, General Electric, Earth Satellite Corporation, Electromagnetic Systems Laboratory, Spectral Data, Dames and Moore, Hennings, Durham and Richardson and so on. In government, geographers with remote sensing interests are employed in the Bureau of the Census, National Aeronautics and Space Administration, Environmental Protection Agency, the Geological Survey, and many other federal, state and local government entities. The geographic program of the United States Geological Survey is, at present, in the process of concentrating its efforts on land use analysis and the development of standardized, compatible (compatible with existing classification systems and with identifiable features as seen on remote sensing imagery) methods of describing land use on their new nationwide 1:250,000 land use series. This is an extremely significant application of remote sensing technology initiated by geographers within the federal government. The authors feel that there is still an important market for geographers with good remote sensing background in both government and private industry and we see this situation continuing into the foreseeable future.

THE PRESENT IN PERSPECTIVE

Remote sensing in geography has made rapid strides in the last decades along with some major disappointments. Institutions offering courses in remote sensing have increased substantially, however, publication in major reviewed journals within the discipline has lagged and the share of substantive research carried out by geographers may well have declined. It is perhaps unfair, but close to the truth, to say that geography seems to be emerging as a teaching only discipline, unaffected by major research programs. On the other hand, we could suggest that this is merely a transitional phase and that as the teaching programs take hold, research will expand. One could also argue that other disciplines, proportionately, seem to be influenced less by remote sensing as shown by the lesser teaching impact. We are suspicious of all such arguments either way, because they are often based on inadequate and potentially biased and misleading surveys. In short, other than more enumeration of the changes which seem to have taken place we are not sure whether there is a firm basis for either hand wringing or self congratulations for *any* discipline.

What then is the true measure of the impact of a new technology upon the discipline? Is it the proliferation of new courses? The amount of research funds acquired? The number of publications in scholarly journals? The acceptance of the technology by recognized leaders in the discipline? As seen above, we are unsure of what answers in these areas mean. We are sure that there has been a significant increase in the number of remote sensing courses taught in geography and that there is a considerable but unrealized potential for research funding. There have been few reviewed remote sensing publications within the major geographic journals, while geographers continue to contribute to specialized remote sensing journals. Finally, there appears to be a lack of acceptance and use of the technology by recognized leaders in the field though this is somewhat counterbalanced by the significant number of departments seeking competent junior faculty in remote sensing as shown by recent professional advertisements.

Through this mire of conflicting evidence, is it possible that the true measure of remote sensing's impact on geography is dependent upon how well it allows the researcher to more effectively test hypotheses? If so, we must consider the many senior geographers who already have a body of data sources and analysis techniques with which they are comfortable. These sources have served them well and their professional reputations may even be based on their skill in employing them. Why should they change and employ remote sensing data? Now we approach the heart of the problem!

The Theoretical and Practical Role of Remote Sensing in Geography

If we as geographers view ourselves from a somewhat whimsical viewpoint several popular definitions present themselves, including:

- geographers are jacks-of-all trades and masters of none;
- geography is that discipline which when some use is found for part of it they call it something else; and
- geography is as geographers do.

In a more serious vein, geography traces its origins back to the ancient Greeks. It is said that Herodotus (484-425 B.C.) is not only the father of history but of geography as well (Broek, 1966). Herodotus achieved this distinction because he placed historical events within a geographic setting by giving descriptive topographies of the places events occurred. Bernhardus Varenius was among the first to present the structure of geography as a scientific discipline. Varenius proposed a division between what he termed general and special geography. General geography dealing with physical phenomena for which universal laws could be formulated. Special geography examining particular areas or regions of the earth as they derive their character from the interaction of human and physical processes. Although Varneius presented the structure of

geography as a discipline it was Immanuel Kant (1724-1804) who secured its foundations within the framework of the philosophy of science. According to Kant, all knowledge can be seen as basically separable into three categories:

- one which sorts facts into groups according to the kinds of objects or phenomena studied, e.g. the systematic sciences of botany, geology, etc.;
- another which sorts facts to view them in their relationships through time, e.g. the historical sciences; and
- the study of things as they are associated in space, i.e. the province of geographical science.

This Kantian view that spatial analysis is at the center of geographic thinking as the fundamental justification for geography is frequently presented. It is, in fact, the basis for Richard Hartshorne's treatise on the Nature of Geography (1939). Other geographers regard the Kantian view as too simplistic, arguing that each of the divisions of knowledge can be viewed from each of Kant's three vantage points and that geography rather than a basic division of knowledge is more a method of viewing or perceiving the environment.

David Harvey, in his book Explanation in Geography, suggests that the following six explanatory forms are employed in the discipline:

- cognitive descriptions - this may range from simple, primary observations to sophisticated, descriptive statements;
- morphometric analysis - in some ways this may be regarded as a type of cognitive description; one involving a *space-time* relationship rather than a property language;
- cause-and-effect analysis - the insistence that cause-and-effect be established to explain the occurrence of environmental distributions.
- temporal modes of explanation - from causal explanation it is a short step to causal chain explanation which stretch back over a long period of time;
- functional and ecological analysis - exploring phenomena in terms of the role they play within a particular social or environmental organization;
- systems analysis - the basis for describing whole complexes and structures of activities. It is only a short step from analyzing the function of a particular phenomena within an organizational framework to studying the structure of that organization as a system of interlocking parts and processes.

One might reasonably ask what is unique about these? Surely natural and social scientists of any persuasion might say the same of their own branch of knowledge. The authors are aware that there may be debate concerning these forms; nevertheless we accept them here as a basis for structuring the remaining discussion.

Because of the substantial overlap in the six explanatory forms, we combine them as follows:

- 1) cognitive morphometric analysis
- 2) cause and effect analysis
- 3) temporal analysis
- 4) functional and ecological systems analysis

Within each of these we ask:

- what does remote sensing permit the geographer to do now better than he has been able to do in the past,
- what does remote sensing permit the geographer to do now that he was unable to do in the past, and finally,
- what may remote sensing enable us to do in the future which could be of significance to professional and academic geography?

Cognitive Morphometric Analysis: This task may range from simple primary in situ observation where the spatial factor is not important, to complex analyses where the attributes of the data are most significant when viewed in relation to their spatial association with other phenomena. Remote sensing data in a 2-dimensional image format has substantial utility for analyses which are concerned with the spatial location of phenomena. It is normally true, therefore, that the profession is most interested in image format remote sensor data. We restrict our comments here to situations where the geographer is concerned with both attributes of the phenomena and its location in space.

Remote sensing has an important role in providing primary spatial data. However, it cannot always provide data on all the functional categories of information with which a geographer might be concerned. For example, resolution constraints may prohibit a plant geographer from identifying plant species. Such data then must still be acquired in situ. Remote sensing may, however, provide a substantial amount of collateral, surrogate information which may significantly affect the time and quality of the field work required to satisfactorily obtain a given category of data. This points out a fundamental characteristic of remote sensing applied to morphometric analysis problems. It can provide specific functional data and/or be used as a method of stratifying, i.e. regionalizing an area. With multiple scale (i.e. multistage) sampling techniques it is possible to stratify regions and design sampling strategies which maximize both the effectiveness of the imaged data by simplifying analysis and also the geographer's field work by optimizing his time through prior identification of productive areas.

With the understanding that regionalization or stratification is an important role for remote sensing in morphometric analyses, let us next consider the impact of this new technology's synoptic, spatially accurate view on geographic research. This can best be understood by considering the map, which most would agree is geography's unique medium for communicating spatial information. Prior to the development of remote sensing, all maps were compiled from terrestrial observations. Such maps were only as accurate as the field-of-view, instruments, and experiences of the personnel which compiled them. Contrast this with the present situation where the geographer's *basemap*, his mainstay of accurate 2-dimensional communication, is for all practical purposes almost totally derived from a combination of photogrammetric and photointerpretation techniques. In fact, Koeman (1970) and Colvocoresses (1976) have pointed out the obvious spatial errors in pre-remote sensing maps where rivers, mountain ranges, and even the spatial dimension of continents were in error. Thus, remote sensing has allowed the geographer's small scale basemap to become more rigorous. This has been significantly affected by the Landsat satellites which have a semiangle of only 5.76 degrees off nadir yielding essentially orthographic images. Landsat's planimetric spatial fidelity is such that (once it is system corrected to eliminate periodic system errors) it meets national map accuracy standards at a scale of 1:500,000 and in several respects meets 1:250,000 standards as well.

Coupled with this increased capability to accurately locate basemap data is the very important contribution of remote sensing to thematic cartography. The "themes" of data (e.g. land use) capable of being extracted from analysis of a given image may be applied to the previously discussed accurate basemap to improve both the spatial and categorical accuracy of the geographer's thematic map.

As a result of this direct impact on map theory, cartographers more than any other body of practicing geographers understand the eventual role remote sensing will have in geography. This is because they are often required out of necessity to understand and utilize remote sensing technology. Consequently, it is not surprising that 38 percent of the 60 geographers teaching remote sensing in the United States in 1976 listed cartography as one of their specialties (AAG, 1976). In the late 1960's and early 1970's numerous articles on "image processing" began to appear in cartographic journals (Muehrcke, 1972; Monmonier, 1976) and data handling symposia (Tomlinson, 1972). In effect, cartographers understand that whether one deals with a map or a photograph is immaterial. The fundamental goal is to communicate the information contained in each so a meaningful conclusion can be drawn. Thus, we find both cartographers and remote sensing specialists concerned with essentially the same topics. First, how to collect the information either in the field or with a sensor system; second, how to portray it, i.e. either in map, image, or digital format; and last, how to interpret and communicate the results be it in a map or image format. With so much in common it is understandable that numerous essentially cartographic problems have been addressed and answered within the realm of remote sensing research during the last decade. Of even more importance, however, might be the new questions, which will tax both sets of researchers in terms of the geobase information systems to be discussed shortly.

Interestingly, most geographer cartographers and remote sensing practitioners feel a certain amount of sympathy for one another. Cartographers for a long time had to struggle within geography with the important yet tattered title of "technique." Remote sensing is serving a similar apprenticeship. Frankly, it is surprising that these two fields of study which are so important to geography and science in general should constantly have to justify their existence. Without either, researchers conducting morphometric analyses would have primitive data collection, analysis, and display capabilities.

Cause-and-Effect Analysis: Obviously, the synoptic view just discussed has important implications for regional studies which attempt to identify cause-and-effect relationships between phenomena *visible* on the landscape. In addition, using sensor systems sensitive to electromagnetic energy outside the visible portion of the EMR, it may be possible to enhance our capability to determine causation, define causal principles, or enunciate causal determinism by facilitating our ability to perceive effects which are beyond our visual experience. Man has always perceived the end results of processes acting on his surroundings (effects) and attempted rational explanations based on his current level of knowledge, experience, and understanding. Remote sensing offers the important capability to extend our detection and understanding of effects which were until now basically beyond the limits of our perception and effective measurement. For example, a thermal infrared scanner can record temperature differences in a river to pinpoint the location of a thermal plume undetectable to the unaided human eye. Similarly, reflective near-infrared photography has been used to detect biophysical stress (i.e. effect) before the cause (e.g. loss of moisture from pathogens) is detectable in the visible region of the spectrum. Such cause-and-effect relationships demonstrate how remote sensing can allow geographers to conduct research on topics previously difficult, if not impossible, to obtain data on.

In addition to the multispectral attributes present in a given cause-and-effect relationship, the ability to perceive the simple geometric shape of phenomena as they progress or regress is important. For instance, the geometry of suburban sprawl, insect infestation, flood inundation, fault related topography, erosion, etc., as they appear on successive synoptic images represent valuable sources of information which may be used to identify cause-and-effect relationships. Without such data the researcher may be seriously handicapped, making conclusions based on sampling networks whose power could potentially be significantly increased through the use of imagery at a number of scales and resolutions from a variety of sensor systems operating at wave-lengths throughout the electromagnetic spectrum. This potential of remote sensing, however,

has still not been substantively implemented by geographers but we anticipate that the new space systems of the 1980's (Landsat-D, Seasat, Radar) will demonstrate practicality.

Finally, remote sensing, because of its multispectral, multitemporal, multi-stage, synoptic nature, may help us avoid the problem of over extrapolation of causal conditions thereby making false inferences as to effects. Even when a cause and effect model has been employed successfully in a number of cases, it is dangerous to believe this is the only model open to the researcher in analysis and explanation or that the real world is totally governed by a unique cause and effect law. Basically the more information concerning reality we can obtain from remote sensing the more likely we are to avoid this pitfall.

Temporal Modes of Explanation: One of remote sensing's most important contributions to geographic research is its ability to provide repeatable observations of phenomena in space. The acquisition of single or multiple image data sets depends upon whether the geographer is concerned with static or dynamic phenomena. If static (e.g. soils, slope, rock type), a single record may be sufficient. If dynamic, the temporal resolution of numerous sensor systems is improving to the point that certain dynamic processes (e.g. runoff, flooding, differential plant response to moisture, etc.) might be effectively modeled. In addition, by interrogating an interaction matrix between static and dynamic phenomena driven with remote sensing supplied data, much detailed information concerning the functioning of both static and dynamic elements present in a given landscape might be achieved. In traditional geographic research, the high temporal resolution required to drive such models is obtainable only by extensive, costly data collection platforms (DCP's) and/or field work. The first remote sensing aided models which attempt to systematically acquire data with a high temporal resolution context are currently being evaluated and results to date appear promising.

"Change" to geographers is synonymous with process. Thus, to be able accurately and consistently to identify change in a *spatial* framework is an important part of any morphometric cause-and-effect investigation. The identification of change in most existing data is difficult because the data is not internally consistent through times (consider the problem of the census with changes in categories, areas and so on which plague longitudinal studies). Landsat data, however, is a unique, internally consistent, longitudinal (i.e. temporal) data set. As long as the system does not change then geographers will have an entirely new alternative to identifying rapid change. Let us evaluate the internally consistent nature of Landsat which promotes regional change detection. It is in a sun-synchronous orbit imaging the same geographic area once every 6 and 9 days at exactly the same time, scale, geometry, look angle, and sensor configuration. Consequently, change of a great diversity of phenomena may be assessed rapidly through multi-date subtraction techniques or through ratioing channels of different dates.

Through multiple date change detection geographers will be able to quantify the rate and geometry of many processes at work in our environment. Probably the biggest handicap to this application, however, will be the requirement that investigators be familiar with the imaged data (in either analog or digital formats) to be interfaced with their traditional non-remote sensing data sets (e.g. the census). This topic will be addressed in the following section.

Functional and Ecological Systems Analysis: All the previous roles of remote sensing in geography may be brought to bear in this the final significant realm of explanatory endeavor. It is here that the data must be transformed into meaningful information useful to the understanding of a process or to make a decision. Just because geographers often require spatially accurate data on either micro or macro-scale phenomena, does not mean that efficient, effective, or accurate methods exist for collecting these data. Remote sensing offers this potential and it is beginning to be applied to systems analysis at both ends of the spatial continuum. For instance, the authors, other geographers and scientists in other disciplines with remote sensing backgrounds are examining the information gained by the application of distributed rather than lumped parameter models to a number of physical processes and cultural phenomena (e.g.

world-wide crop inventories, monitoring snowmelt runoff, developing models for monitoring urban expansion and energy consumption). Although data on these processes and phenomena were previously available through conventional procedures, their use coupled with the spatial and spectral dimension added via remote sensing has added significantly to their information potential.

In particular, the development of sophisticated geobase information systems has begun (Bryant, 1976). Until recently, geobase information systems essentially lacked data of a quality, quantity, and timeliness to adequately drive the systems. Remote sensing is capable of providing internally consistent data in a format and time framework compatible with the range of data inputs required. However, there exist some serious obstacles yet to be surmounted if the incorporation of remote sensing is to have a significant impact on geographic systems analysis. First, one of the major discoveries in working with Landsat data has been that even at its current 80m spatial resolution it provides data of such spatial detail and specificity that existing models cannot accommodate the data. Among the areas where investigators are now improving existing models to incorporate the remote sensing data are:

- hydrologic models incorporating landcover and land use data;
- agricultural models concerned with water demand, yield and stress;
- agrometeorological models within which remote sensing performs a confirmation, weighting or calibration function, and;
- descriptive and predictive models of land use change based on frequent updating.

A review of the previous list will reveal a serious gap in the modeling realm. Other than crop yield, note the serious lack of attempts to incorporate remote sensing into economic modeling. The primary reason for this is that economic geographers have the census available which is a first-rate source of information. Therefore, why be concerned with remote sensing? Remote sensing can perform the important role of "unpacking" the highly aggregated census data in both space and time. For instance, a researcher may be using a population density statistic for a given census tract which is spatial in nature but highly aggregated. By incorporating heterogeneous land use data derived from remote sensing it is possible to unpack the census tract data allowing the researcher to know which spatial regions within the tract account for most of the variance. In effect, both the census and remote sensing data become calibrated and may be used with change detection and future land use modeling to provide a variety of social and economic statistics of importance to economic geographers. In this respect it is important for economic geographers to note that the Census itself is presently funding studies to test how the merging of Landsat and census data can improve the latter.

Thus we find that remote sensing may play an integral part in systems analysis wherein it may function as a "linch pin" to interface meteorological, social, economic, and physical data together for effective modeling purposes. As previously noted, however, cartographers and physical geographers currently account for most serious basic and applied remote sensing research. Economic and regional geographers, on the other hand, are not utilizing remote sensing technology. The burden falls heavily, therefore, on those geographers who are cartography/remote sensing technologists to interface with the regional and economic geographers. In this manner our colleagues may begin to incorporate the information available through remote sensing into their research.

A CONCLUDING LOOK AT THE FUTURE

H.V.B. Kline, Jr., writing on the prospects for air photo interpretation in American Geography Inventory and Prospect (James and Jones, 1954), quotes John E. Kesseli as saying, "Only in departments so sufficiently staffed to consider all parts of the geographic field can it be expected that air photography has

found, or may find, its due consideration as a research field." Furthermore, the student "...is inclined to neglect field and laboratory courses which provide a training in the gathering and interpretation of information, hoping that his problem will take care of itself when the time for independent research arrives." Hopefully, in geography this situation is changing.

At the 1964 conference sponsored by the National Academy of Science National Research Council, L.A. Peter Gosling described an "air of enthusiasm which inspired panel members to work eagerly and imaginatively on their respective reports." This meeting brought together at a critical early stage in the United States space program the talents of a number of distinguished geographers to make recommendations on the potential of the newly developing field of spacecraft research as tools for the geographer. Statements as: "The opportunity to obtain synoptic, regularly repeated views of the whole earth and the changing surface of the lands and seas will have a profound effect on the growth and internationalization of geographic sciences," illustrate the level of potential realized by these leaders in the field. It is a pity that more of these individuals did not maintain their enthusiasm.

The improved or unique information available to the geographer via the application of remote sensing techniques has barely begun. Yet, when thoughtfully analyzed it can be seen to provide the geographer with significant improvements in the quantity, quality, and timeliness of data required. As more geographers become aware of the significant implications of remote sensing for providing such data the true impact of this technique in the discipline will be felt. Remote sensing, like cartography, is rapidly approaching a state of technology and body of coherent knowledge almost to be viewed as a discipline in and of itself. What is required to increase the impact of remote sensing in geography is a concerted effort on the part of geographers and others who specialize in remote sensing to conduct their research more thoughtfully so as to more effectively impact their disciplines.

Remote sensing is a reality within geography whose time has come. It is too powerful a tool to be ignored in terms of both its information potential and the logic implicit in the reasoning process employed to analyze the data. When allied with the traditional cornerstone of geography, i.e. cartography, in its new digital raiment, the two techniques will go far beyond being mere technologies. We predict they will change our perceptions, methods of data analysis, models, and our paradigms.

Harkening back to the introduction of this paper, although some geographers decry the lack of impact of remote sensing on the discipline, the authors do not agree. In the perspective of time and viewed in the larger picture of the impact of remote sensing on all disciplines, remote sensing's impact on geography has already been significant and may in the future be profound.

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TABLE I
INSTITUTIONS WITH GEOGRAPHY OFFERINGS IN
AIR PHOTO INTERPRETATION/REMOTE SENSING

STATE	NAME OF UNIVERSITY	1950-51	1960-61	1971-72	1975-76	STATE	NAME OF UNIVERSITY	1950-51	1960-61	1971-72	1975-76
Alabama	Univ. of Alabama, Tuscaloosa	•	•	•	•	New York (cont.)	State Univ. of New York, Binghamton	•	•	•	•
Arizona	Arizona State Univ., Tempe	•	•	•	•		State Univ. of New York, Plattsburgh	•	•	•	•
	N. Arizona Univ., Flagstaff	•	•	•	•		State Univ. College, Buffalo	•	•	•	•
	Univ. of Arizona, Tucson	•	•	•	•		State Univ. College, Cortland	•	•	•	•
California	California State Univ., Chico	•	•	•	•		State Univ. College, New Paltz	•	•	•	•
	California State Univ., Dominguez	•	•	•	•	North Carolina	State Univ. College, Oswego	•	•	•	•
	California State Univ., Fresno	•	•	•	•		Syracuse Univ., Syracuse	•	•	•	•
	California State Univ., Fullerton	•	•	•	•		Appalachian State Univ., Boone	•	•	•	•
	California State Univ., Hayward	•	•	•	•		East Carolina Univ., Greenville	•	•	•	•
	California State Univ., Los Angeles	•	•	•	•		Univ. of N. Carolina, Chapel Hill	•	•	•	•
	California State Univ., Northridge	•	•	•	•		Univ. of N. Carolina, Charlotte	•	•	•	•
	California State Univ., San Diego	•	•	•	•	North Dakota	Univ. of North Dakota, Grand Forks	•	•	•	•
	California State Univ., San Jose	•	•	•	•		Bowling Green State Univ., Bowling Green	•	•	•	•
	Humboldt State Univ., Arcata	•	•	•	•	Ohio	Kent State Univ., Kent	•	•	•	•
	Sonoma State College, Rohnert Park	•	•	•	•		Miami Univ., Oxford	•	•	•	•
	Univ. of California, Davis	•	•	•	•		Washington College, New Concord	•	•	•	•
	Univ. of California, Los Angeles	•	•	•	•		Ohio Univ., Athens	•	•	•	•
	Univ. of California, Riverside	•	•	•	•		Univ. of Akron, Akron	•	•	•	•
	Univ. of California, Santa Barbara	•	•	•	•		Wittenberg Univ., Springfield	•	•	•	•
Colorado	Adams State College, Alamosa	•	•	•	•	Oklahoma	Wright State Univ., Dayton	•	•	•	•
	S. Colorado State College, Pueblo	•	•	•	•		East Central State College, Ada	•	•	•	•
	US Air Force Acad., Colorado Springs	•	•	•	•		Univ. of Oklahoma, Norman	•	•	•	•
	Univ. of Colorado, Boulder	•	•	•	•	Oregon	Oregon State Univ., Corvallis	•	•	•	•
	Univ. of Colorado, Denver	•	•	•	•		Portland State Univ., Portland	•	•	•	•
Connecticut	Univ. of Connecticut, Storrs	•	•	•	•		Univ. of Oregon, Eugene	•	•	•	•
Delaware	Central Conn. State Coll., New Britain	•	•	•	•	Pennsylvania	Indiana Univ. of Penn., Indiana	•	•	•	•
D.C.	Catholic Univ. of Am., Washington, D.C.	•	•	•	•		Lock Haven State College, Lock Haven	•	•	•	•
Florida	Florida Atlantic Univ., Boca Raton	•	•	•	•		Penn. State Univ., State College	•	•	•	•
	Florida State Univ., Tallahassee	•	•	•	•		Temple Univ., Philadelphia	•	•	•	•
	Rollins College, Winter Park	•	•	•	•	South Carolina	Univ. of Pittsburgh, Pittsburgh	•	•	•	•
Georgia	Univ. of Florida, Gainesville	•	•	•	•		Univ. of South Carolina, Columbia	•	•	•	•
	Univ. of Georgia, Athens	•	•	•	•	South Dakota	South Dakota State Univ., Brookings	•	•	•	•
	W. Georgia College, Carrollton	•	•	•	•	Tennessee	East Tenn. State Univ., Johnson City	•	•	•	•
Hawaii	Univ. of Hawaii, Honolulu	•	•	•	•		Memphis State Univ., Memphis	•	•	•	•
Idaho	Univ. of Idaho, Moscow	•	•	•	•	Texas	Univ. of Tennessee, Knoxville	•	•	•	•
Illinois	Augustana College, Rock Island	•	•	•	•		North Texas State Univ., Denton	•	•	•	•
	Illinois State Univ., Normal	•	•	•	•		N. Texas State Univ., San Marcos	•	•	•	•
	N. Illinois Univ., Chicago	•	•	•	•	Utah	Univ. of Texas, Austin	•	•	•	•
	Northern Illinois Univ., DeKalb	•	•	•	•		Brigham Young Univ., Provo	•	•	•	•
	Northern Illinois Univ., Evanston	•	•	•	•		Univ. of Utah, Salt Lake City	•	•	•	•
	S. Illinois Univ., Carbondale	•	•	•	•	Vermont	Univ. of Vermont, Burlington	•	•	•	•
	S. Illinois Univ., Edwardsville	•	•	•	•	Virginia	Mary Washington College, Fredericksburg	•	•	•	•
	Univ. of Illinois, Urbana	•	•	•	•		Univ. of Virginia, Charlottesville	•	•	•	•
	W. Illinois Univ., Macomb	•	•	•	•	Washington	Central Wash. State College, Ellensburg	•	•	•	•
Indiana	Anderson College, Anderson	•	•	•	•		East Wash. State College, Cheney	•	•	•	•
	Ball State Univ., Muncie	•	•	•	•		Univ. of Washington, Seattle	•	•	•	•
	Indiana State Univ., Terre Haute	•	•	•	•	Wisconsin	Western Wash. State College, Bellingham	•	•	•	•
	Indiana Univ., Bloomington	•	•	•	•		Beloit College, Beloit	•	•	•	•
	Indiana Univ., SE, Jefferson	•	•	•	•		Cardinal Stritch College, Milwaukee	•	•	•	•
	Indiana Univ., NW, Ellettsburg	•	•	•	•		Univ. of Wisconsin, Green Bay	•	•	•	•
Iowa	Univ. of Iowa, Iowa City	•	•	•	•		Univ. of Wisconsin, La Crosse	•	•	•	•
Kansas	Univ. of Kansas, Lawrence	•	•	•	•		Univ. of Wisconsin, Madison	•	•	•	•
	Univ. of Kansas, Wichita	•	•	•	•		Univ. of Wisconsin, Milwaukee	•	•	•	•
Kentucky	Eastern Kentucky Univ., Richmond	•	•	•	•		Univ. of Wisconsin, Oshkosh	•	•	•	•
	Univ. of Kentucky, Lexington	•	•	•	•		Univ. of Wisconsin, Platteville	•	•	•	•
	Univ. of Louisville, Louisville	•	•	•	•		Univ. of Wisconsin, Stevens Point	•	•	•	•
	Western Kentucky Univ., Bowling Green	•	•	•	•	Wyoming	Univ. of Wisconsin, Whitewater	•	•	•	•
Louisiana	Louisiana State Univ., Baton Rouge	•	•	•	•		Univ. of Wyoming, Laramie	•	•	•	•
	Louisiana State Univ., Shreveport	•	•	•	•						
	Nicholls State Univ., Thibodaux	•	•	•	•						
	Southern Univ., Baton Rouge	•	•	•	•						
Maryland	Frostburg State College, Frostburg	•	•	•	•						
	Towson State College, Towson	•	•	•	•						
	Univ. of Maryland, College Park	•	•	•	•						
Massachusetts	Boston Univ., Boston	•	•	•	•						
	Clark Univ., Worcester	•	•	•	•						
	Fitchburg State College, Fitchburg	•	•	•	•						
	Framingham State College, Framingham	•	•	•	•						
Michigan	Central Michigan Univ., Mt. Pleasant	•	•	•	•						
	Michigan State Univ., East Lansing	•	•	•	•						
	Northern Michigan Univ., Marquette	•	•	•	•						
	Western Michigan Univ., Kalamazoo	•	•	•	•						
Minnesota	Mankato State Univ., Mankato	•	•	•	•						
	Moorhead State College, Moorhead	•	•	•	•						
	St. Cloud State College, St. Cloud	•	•	•	•						
	Univ. of Minnesota, Minneapolis	•	•	•	•						
Mississippi	Mississippi State Univ., Mississippi	•	•	•	•						
	Univ. of Southern Miss., Hattiesburg	•	•	•	•						
Montana	Montana State Univ., Bozeman	•	•	•	•						
	Univ. of Montana, Missoula	•	•	•	•						
Nebraska	Univ. of Nebraska, Lincoln	•	•	•	•						
	Univ. of Nebraska, Omaha	•	•	•	•						
	Univ. of Nevada, Las Vegas	•	•	•	•						
Nevada	Dartmouth College, Hanover	•	•	•	•						
New Hampshire	Princeton Univ., Princeton	•	•	•	•						
	Rutgers Univ., New Brunswick	•	•	•	•						
New Jersey	New Mexico State Univ., Las Cruces	•	•	•	•						
New Mexico	Univ. of New Mexico, Albuquerque	•	•	•	•						
	Briarcliff College, Briarcliff Manor	•	•	•	•						
	Columbia Univ., New York	•	•	•	•						
New York	Hunter College, New York	•	•	•	•						
	State Univ. of New York, Albany	•	•	•	•						

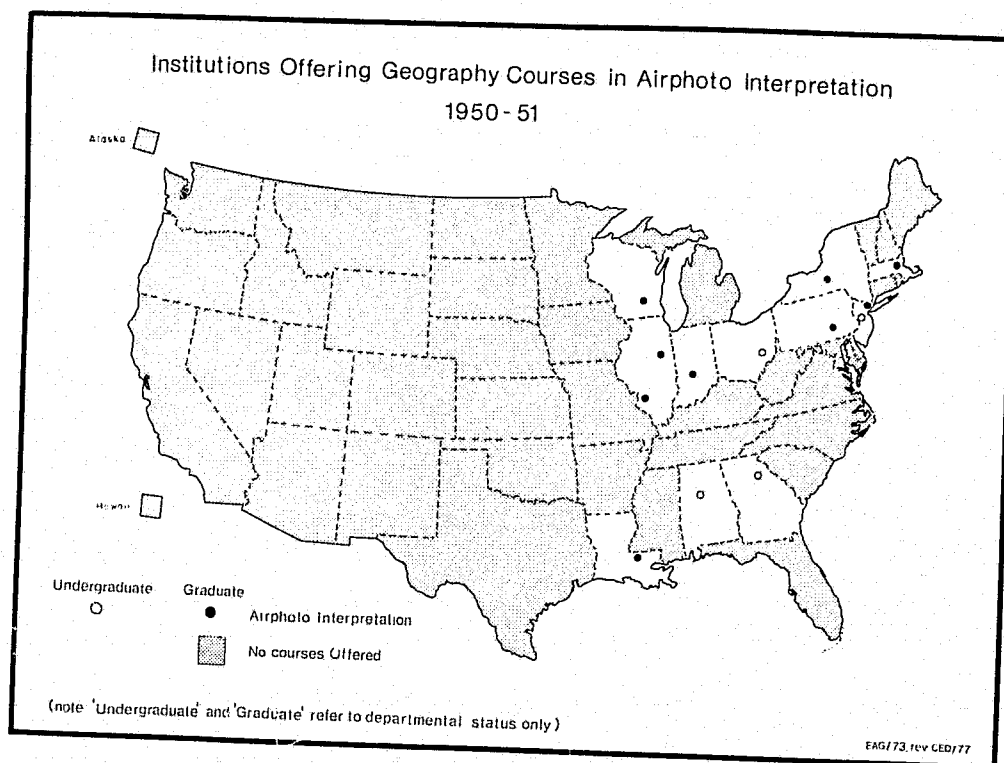


FIGURE 1

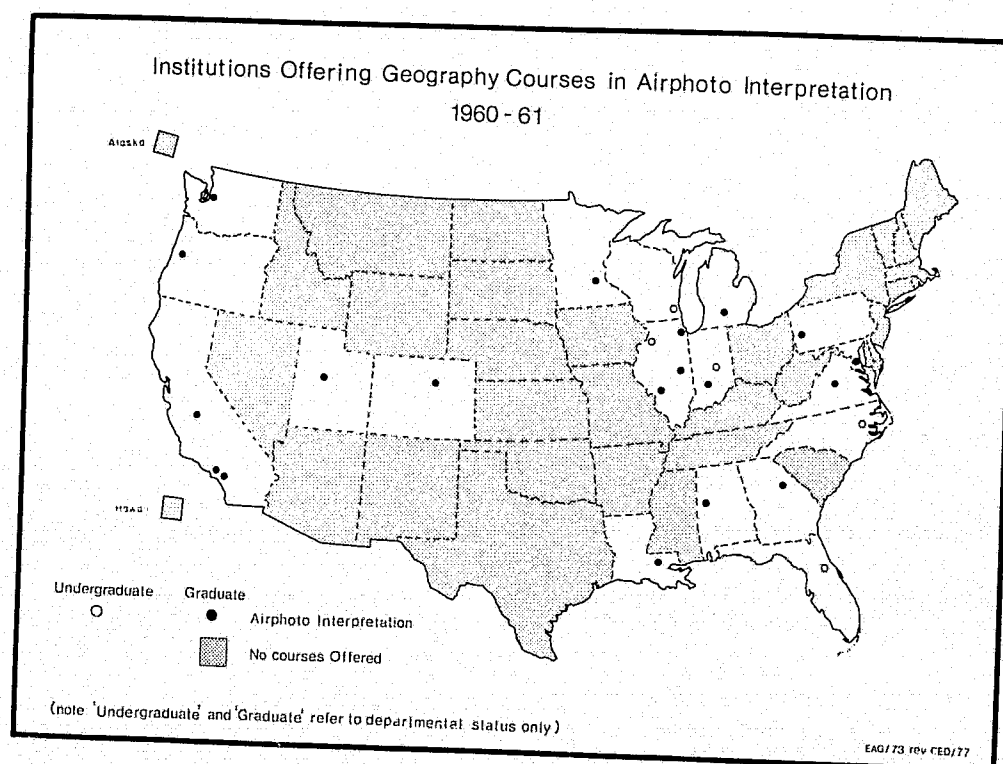


FIGURE 2

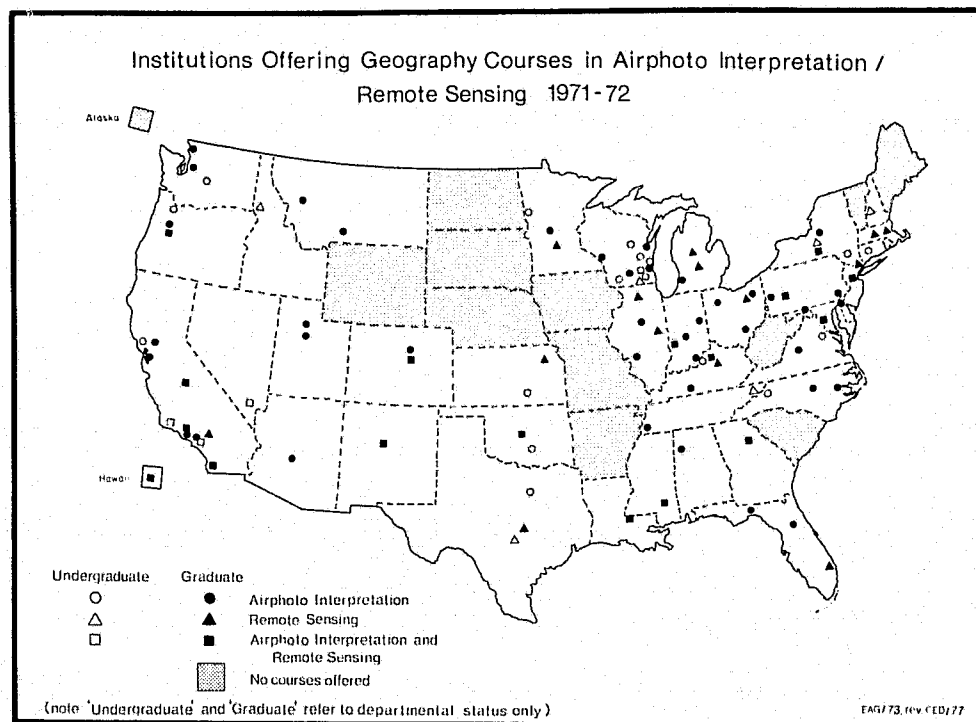


FIGURE 3

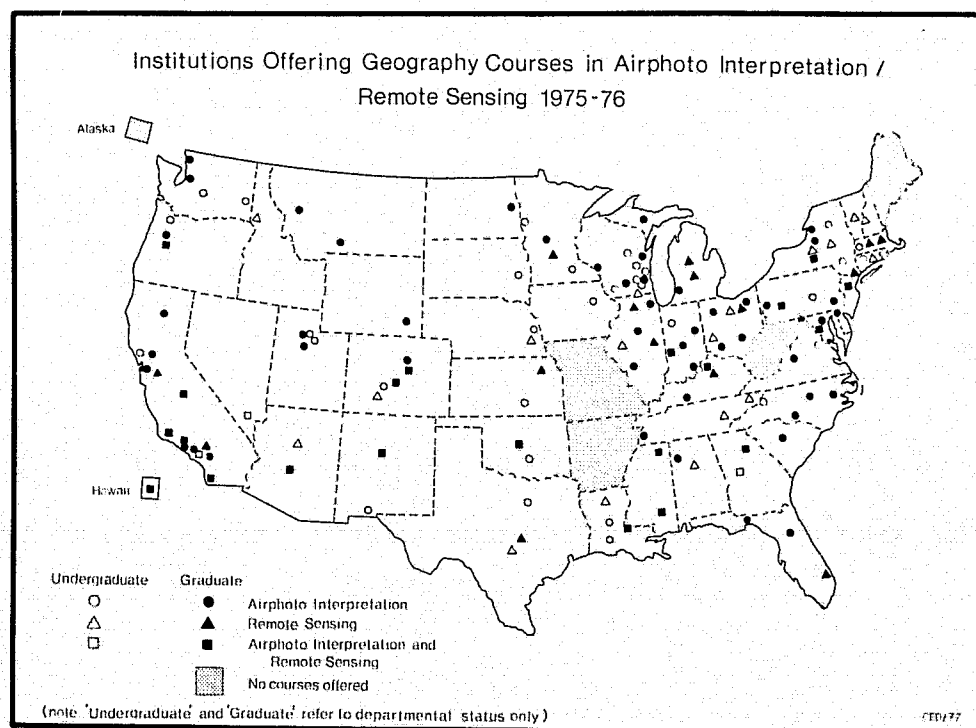


FIGURE 4

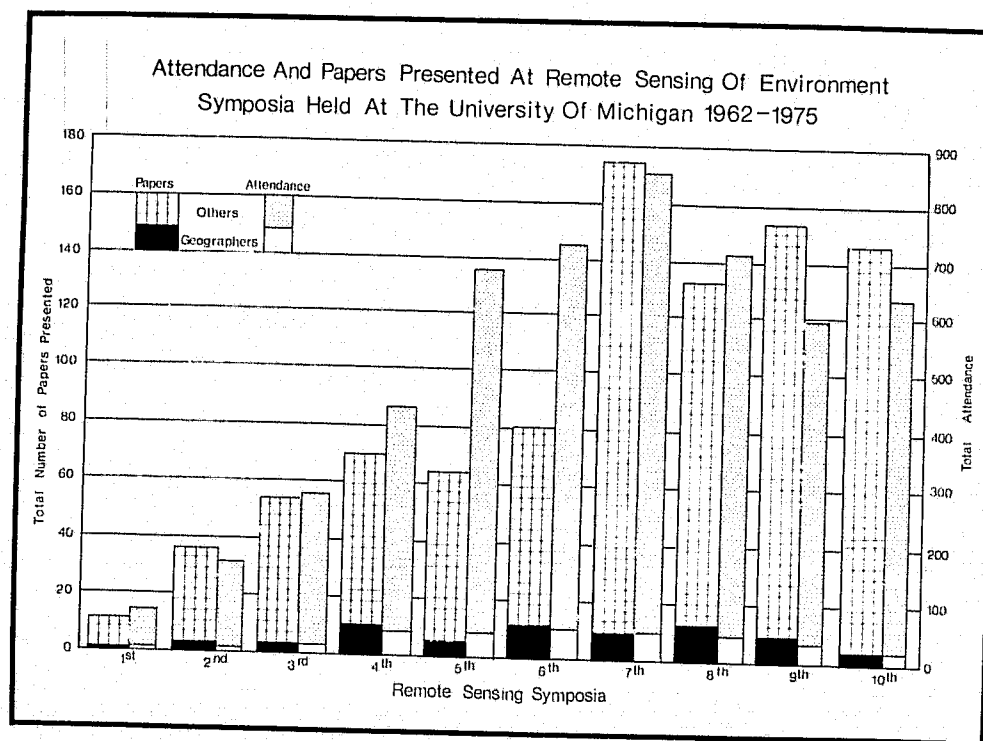


FIGURE 5

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REMOTE SENSING IN GEOGRAPHIC APPLICATIONS

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ABSTRACT

During the past ten years, geographers have been involved in a range of activities that include remote sensing as a data-gathering tool. Examples of geographic applications of remotely sensed data include problem-solving, geographic training, and research. Sample demonstrations have dealt with mapping urban land use from a variety of sensors; assessing housing quality; monitoring Savannah grassland fires; defining the urban "heat island;" assessing flood damage to irrigated and non-irrigated cropland; correlating land use by census tract with contemporaneous data from the census, and then monitoring changes; conducting remote sensing workshops for professional groups and user agencies; and preparing a guide for using remotely sensed data for land use mapping and inventory.

Lists of statistical data or computer generated maps illustrate the kinds of products obtainable using digital remotely sensed data. Our examples include products resulting from manual and semi-automated compilation techniques, whose characteristics include the possibilities for statistical analysis, reproduction, and update of time-series data. The examples also demonstrate geographic information systems development in response to remote sensing data, as well as to changes in graphic and digital cartography. In contrast to engineering cartographers, geographers have been more interested in the extraction of thematic, spatial or areal information from remotely sensed data, and the subsequent creation of apparent spatial structures.

As the incumbent spatial discipline, Geography responded (positively or negatively) to the opportunities which remote sensing technology and the space exploration program presented during the last decade. Some of these opportunities have been seized upon, some have been abdicated, others have been ignored, and still others have been pursued within the discipline. These trends are documented by posing and answering the following questions:

- 1) What new applications of geography as a spatial discipline have evolved?
- 2) What old applications have been made more efficient?
- 3) What influence has remote sensing had on the use of other geographic tools?
- 4) What influences has remote sensing had on cartographic techniques, accuracy, data presented, concepts, etc.?

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REMOTE SENSING DATA PROCESSING - TWO YEARS AGO,
TODAY, AND TWO YEARS FROM TODAY

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ABSTRACT

Perhaps the most intriguing characteristic of science is the inability of even active participants to accurately predict what lies in store "over the horizon." Using the simplification that developments in Remote Sensing data processing represent a continuum, we compare the state-of-the-art in early 1975 with that of early 1977 and surmise where our technology will be in early 1979. In doing this, we accept the limitation that in all likelihood, the most significant development of the next two years has not been included in our projections. Not included, because the truly significant developments often stem from unexpected breakthroughs which redirect the very mainstream of the underlying technology.

To some users, Remote Sensing data processing is just another element, like the sensor system itself, which stands between them and the quantitative information they need to know about a complex ground scene. But we who aspire to help Earth resource Remote Sensing fulfill its tremendous potential, regard data processing as an extension of the human mind. For only when the processing of remotely sensed data is lifted out of the realm of mathematical algorithms and the hardware/software environment in which these algorithms are embedded can the basic purpose be seen. That purpose is to provide timely and accurate information from an extensive area at a cost that is worth paying.

1. INTRODUCTION

The future for Remote Sensing information extraction and analysis is looking bright. But before one can claim to foretell its future, one must consider both the setbacks and advances of the past two years. Beginning with a survey of the state-of-the-art of remote sensing data processing in early 1975, we chronicle the significant developments between that time and today, then go on to project where our technology may be in early 1979. In order to make such a projection, a certain continuity must be assumed. Because of this assumption, our projections must necessarily leave out any unexpected breakthroughs which redirect the very mainstream of the underlying technologies.

2. WHERE WE WERE IN 1975

When Landsat II was launched in January of 1975, many of us felt that we truly understood what lay ahead of us. Widespread experience with ERTS data [1], confidence that the maximum likelihood classification rule was indeed ultimate, pride in the new generation of interactive image processing systems [2] that were being developed, and the beginning flow of data in an ambitious Tri-Agency project called LACIE which would utilize multitemporal Landsat data and no ground truth to inventory the wheat crop in several countries, all combined to give us a sense of order and focus.

At that time, we were aware that the history of multispectral data processing was primarily a long sequence of feasibility studies. A typical scenario for such a study might go as follows: An individual researcher would acquire a data set and spend several months trying vainly to obtain results by following a preconceived analysis plan. Then, while investigating the reason for this apparent failure, a revised technique would be discovered that gave excellent correlation with the surface cover of interest. Voila! Feasibility was demonstrated and the experiment would be written up for either a learned journal or a presentation at a Remote Sensing Symposium, such as this one. Naturally, such scientific success merited follow-on funding and further feasibility testing on a new data set. More often than not, the arrival of a new data set would once again be followed by several months of vainly trying to obtain comparable results. Back then, many of us became very adept at explaining how each new data set was different from our previous data sets.

While feasibility studies left us a bit uneasy, our confidence was undiminished in early 1975 because we were convinced that valuable information about the Earth's resources could be obtained over sizable areas by means of remote sensing. Environmental awareness and the demand for sound land use management required such information and, in our opinion, the only economical way to provide it was via an information system based upon remotely sensed data. Here also, there was somewhat of a disparity between dream and reality. Although tentative cost-benefit studies had long indicated that for large areas remote sensing would be cost effective, the "user community" was not actively seeking assistance from remote sensing. In retrospect, it seems a strange thing that we should have felt so confident about the existence of a well-defined "user community" when the various groups we wanted to include as users were unsure as to how remote sensing could be of any real help to them.

Let us imagine that a hypothetical user had set out in January of 1975 to visit each of the many groups involved in the analysis of multispectral scanner data. Their journey would have taken them across the U.S. from the NASA Data Processing Facility in Greenbelt, Maryland, to the Jet Propulsion Lab in California, North to the University of Alaska in Anchorage, and then East to the Canada Centre for Remote Sensing in Ottawa, Canada, with many major stops in-between. Through such a grand tour, this hypothetical user would have learned of potential MSS applications ranging from urban growth, agriculture and rangeland, to forestry, geology, water quality and even the inventorying of the breeding habitat of migratory waterfowl in North Dakota and the Arctic Islands [3].

Continuing in this same vein, let us suppose that our sojourning user had a penchant for mathematics and wherever he visited, he would ask questions such as, "What approaches do you find best suited for data analysis?", "How long does it take to analyze ERTS MSS imagery from, say, a 30 square mile area?", and "What are the technical difficulties which must be overcome before this technology can be transferred from a Research and Development environment to operational use?" Let us examine these three questions individually, for even within a single institution, our hypothetical user would have received conflicting answers.

What Approach is Best Suited for MSS Data Analysis? (Circa 1975)

Although some of the most cost-effective applications of remote sensing in early 1975 stemmed from manual interpretation of false color ERTS imagery, the majority of researchers favored an interactive approach wherein a computer was used to apply a series of treatments to multispectral scanner data under the

controlling hand of a skilled researcher. Needless to say, the treatments or algorithms employed depended upon the application. They also depended rather dramatically on the computational facility available. Those of us with access to large computers used interactive displays and ground observations for training field delineation followed by iterative clustering to refine training statistics before employing a quadratic (maximum likelihood) classifier on the area of interest. Some researchers, with more modest computing facilities, used channel selection techniques to reduce computational load during maximum likelihood classification. Others sought best linear combinations of channels, or employed non-parametric classifiers, or linear discriminants to reduce the computational burden during classification. It was tacitly assumed that sufficient additional information was available to enable the researcher to judge the validity of the final result.

How Long to Analyze ERTS MSS Imagery from 30 Square Miles? (Circa 1975)

Table I gives representative central processor times and memory requirements (circa January 1975) for data analysis of a four channel MSS image containing 23,000 picture elements.

TABLE I. REPRESENTATIVE REQUIREMENTS (CIRCA JANUARY 1975)
FOR DATA ANALYSIS OF A FOUR CHANNEL MSS IMAGE
CONTAINING 23,000 PIXELS ON ERIPS

	<u>CPU Time</u>	<u>Memory</u>
ISOCCLASS ITERATIVE CLUSTERING (Seven Iterations, up to Twenty Clusters)	~22 minutes on an IBM 360/75	200,000 32-bit words
Maximum Likelihood Classifica- tion into Twenty Classes	~ 2 minutes on an IBM 360/75	150,000 32-bit words
Feature Selection Based on Divergence Criteria (For Twenty Classes)	~ 2 minutes on an IBM 360/75	100,000 32-bit words

To put these times into perspective, we note that, back then, several classification attempts were usually required to achieve acceptable results. Since 23,000 pixels was less than $1/80^{\text{th}}$ of a standard ERTS Computer Compatible Tape, Eppler's [4] or Shlien and Smith's [5] Table Look-up implementation of a maximum likelihood classifier was very attractive for digital processing of full ERTS frames. The notion here was that since a Landsat scene typically has only about 10,000 unique 6-bit vectors (unless snow is present, in which case there are about 100,000 vectors), these unique vectors can be classified and the results used to create a look-up table. The payoff is typically a 35/1 reduction in CPU time for classification.

What Technical Difficulties Must be Overcome to Achieve Operational Data Processing (Circa 1975)

Table II lists the technical issues which seemed very important in early 1975.

The effect of physical factors on MSS data gathered from a satellite is significantly less than for data acquired from an aircraft. Yet, everyone recognized that some way of characterizing and minimizing data variability due to differences in observation conditions was required. The technical issue was whether or not an adequate characterization could be done using the limited data available.

Early in 1975, those of us who were still removing noise from the scanner data collected during SKYLAB were anxious to analyze ERTS-B preflight imagery to avoid a similar experience with Landsat. Holmes was convinced that good data quality was the key and spent the majority of his time in this area. The

technical issue was whether or not a reasonable range of results could be guaranteed given high quality of the input data.

TABLE II. TECHNICAL ISSUES (Early 1975)

- PHYSICAL FACTORS (Sun Angle, Atmospheric Effects, Background Albedo)
- DATA QUALITY (Sensor Noise, Cloud Cover/Haze, Frequency of Observation)
- TRAINING SELECTION AND LABELING
 - Ground Truth vs Image Interpretation
 - Signature Extension/Partitioning
- SAMPLING SCHEMES (for accurate prediction)
 - Spatial Resolution
 - Spectral Resolution
- CLASSIFICATION (Unitemporal vs Multitemporal)
 - Optimum Time(s)
 - Influence of Misregistration
- SYSTEM THROUGHPUT (The price of processing a sufficient amount of data to permit a significant conclusion.)

Pattern recognition implies training. The high cost of collecting ground truth and the severe limitations associated with only being able to accurately process data with associated ground truth gave rise to the quest for alternatives. One issue was whether or not a skilled photo-interpreter, equipped with currently available information could adequately select and label training fields in satellite data. Once a classifier was trained, related technical issues were, "Could the region (partition) for which this training was valid be characterized?" and "Could these regions of validity be extended?" (signature extension).

There were corresponding technical issues in the areas of sampling schemes for accurate prediction, information content required for classification to yield accurate discrimination and a concern that conclusions be based upon a consistent procedure applied to a sufficient amount of data to be significant.

Early in 1975 each of us had our own conception of what was needed to make remote sensing come of age. Some researchers were concerned with how to achieve higher recognition accuracies, other researchers were trying to develop classifiers which would retain the power of the maximum likelihood classifier yet to be free of the underlying assumption of multi-variate normality and, at the same time, execute more rapidly. Some researchers were eagerly awaiting spring so they could monitor the development of rangelands as warm weather moved from south to north, while others were wildly scrounging about to locate the "user" each research institution was expected to display in order to abide by NASA Headquarter's dictum to "make it operational". At NASA's Goddard Space Flight Center a new software system was being developed to reduce the 48 minutes of Sigma-3 time required to extract and correlate a 30 square mile portion of an ERTS scene to an earlier acquisition for LACIE. Meanwhile, at NASA's Johnson Space Center, the mechanics of trying to get data flowing smoothly through the myriad of steps involved in LACIE operations seemed nearly overwhelming.

3. WHERE ARE WE TODAY?

Let us leave our hypothetical user for a while and examine the growth which took place during 1975. Spring came, and Landsat II MSS data was found to be of excellent quality, although its calibration was markedly different from Landsat I.

The green wave advanced from Texas to Canada and was successful in bringing about bumper crops which were not at all disturbed by remote sensing. 1975 was a year of growth for all of us. When Goddard Space Flight Center brought up a system which enabled a LACIE sample segment to be extracted and registered in one-eighth of the previous time, and NASA/JSC began storing these 30 square mile portions of a Landsat scene in a 2.9 billion byte on-line data base so that all acquisitions would be instantaneously available for processing it appeared as though the long-awaited era of quasi-operational use of remotely sensed satellite data was about to dawn. LACIE began with so much confidence only to discover that information extraction from an arbitrary segment of a Landsat image in the absence of ground truth was a far more formidable task than most of us had anticipated.

Holmes recalls a forlorn moment in late April when he honestly wondered if any of the current algorithms would survive to autumn unscathed. Few did. Perhaps it was our naivete, perhaps this was simply the first real opportunity to test these algorithms on a broad geographic scale under a variety of conditions. By late August we could honestly say we were much wiser about the task which lay ahead of us, though many of us would have preferred to be a little less wise and a bit more comfortable.

Although dramatic advances were made during 1975 in the machinery of image processing and pattern recognition, more than anything else we came to a better appreciation of what it was that we didn't understand. The large gap between feasibility studies and quasi-operational use over a large region came home when LACIE found all the classical approaches to signature extension for maximum likelihood classification were totally inadequate.

Those of you who attended this Symposium in October of 1975 heard presentations by Researchers from Switzerland, Sweden, Spain, The Netherlands, Italy, Germany, France, Finland, and Canada. It was pleasing to see such widespread interest and commitment to the ideal of using information extracted from remotely sensed data. For with some of the best minds from all these lands pushing back the frontier, meaningful progress was certain to occur. And so it did in 1976.

In 1976 G. E. Lowitz from France showed us how to characterize principal component images according to their metric content [6] by drawing a quantitative distinction between real image structure and statistical noise fluctuations. It was interesting to note that in addition to significant structure in the principal components associated with the largest three eigenvalues of a seven channel data set, Lowitz observed significant image structure to be present in the principal image associated with the smallest eigenvalue.

In 1976 Starr and Mackworth [7] from the University of British Columbia, Canada made the first inroads in characterizing analytically the use of shape and texture in extracting information from a remotely sensed image. While this work is far from complete, the approach is an exciting one. Indeed, the ability to use context or texture and shape in addition to spectral content is one of the reasons a trained photointerpreter is able to discern so much information from an image [8].

In 1976 the proper setting for large scale agricultural remote sensing based on Landsat data was shown [9] to be a multitemporal setting in which the temporal sampling was matched to the crop calendar. Although the increased dimensionality of these data sets gives rise to added complexity in clustering or adequately training a parametric classifier, the added information content provided by the temporal trends [10] permitted global information extraction and analysis techniques to be successfully employed for the first time.

Because information extraction from remotely sensed data involves processing a relatively large number of individual observations, advances in the underlying computing technology are intimately linked to advances in remote sensing data processing.

For example, the privilege of trying to develop a global approach was non-existent until suitable data sets were assembled. Such large data sets were not assembled until processing facilities [11] equal to the computational task of processing them were developed.

It isn't clear whether increases in the complexity of the information being sought from remotely sensed data come first and the data processing capability to meet these needs is created later, or vice-versa. A typical example is afforded by the growth of the Earth Resources Interactive Processing System at NASA/JSC. As initially developed this system was I/O bound until a special Image Data Access Method [12] was created and installed in early 1975. The system was then CPU bound for most applications until early 1976 when a STARAN parallel processing computer was interfaced [13] to the host computer and it again became I/O bound. This time, however, the limiting I/O function was the rate at which data could be staged to and from the parallel processor. Table III gives representative times for the STARAN equipped system (Circa March 1976) for data analysis of a four channel MSS image containing 23,000 pixels. These times should be compared with Table I. During the past year the computational complexity of the problems being addressed have grown to the point where even this STARAN equipped system will soon cease to be I/O bound!

TABLE III
Representative Times (Circa March 1976) for Data Analysis of a
Four Channel MSS Image Containing 23,000 Pixels on the
STARAN Equipped ERIPS System

	<u>Time</u>
ISOCCLASS ITERATIVE CLUSTERING (Seven Iterations, up to Twenty Clusters)	43.3 seconds
Maximum Likelihood Classification into Twenty Classes	43.1 seconds

More than a dozen interactive image processing systems which were under-going development in 1975 now exist [14], and many of them are available either as standard commercial products or as custom tailored systems with hardware options which are seemingly limited only by the purchasers' budgetary constraints. It is difficult to draw up a meaningful comparison between these systems for although each of them was designed around the interactive concept they range from software packages suited solely for use with a large general purpose computer to highly specialized software/hardware packages structured around a specific model of minicomputer. In 1977 one trend stands out very clearly. Because of advances in processing speed the combination of a minicomputer with an array processor will lead to significantly cheaper image analysis systems.

3.1. CURRENT TECHNICAL ISSUES

The strength of science is in the inquisitive and powerful minds of the individuals who conceive, conduct and interpret the experiments. A list of current technical issues is shown in Table IV. Some of these were issues in 1975.

Pattern recognition can do no better than the training selection and labeling will support. The technical issue today is how should training selection and labeling be done.

For economy of operations effective sampling schemes are needed in both the spatial and temporal domain. Sampling is currently employed, but the effects introduced are largely unknown.

Today, everyone agrees that Landsat classification can be performed to at least the level of different types of vegetation. At issue is the level of

detail at which reliable discrimination can be performed over a large region. There is a need to be able to predict error rates and to eliminate or at least determine biases in classification results so that quantitative statements can be made about the significance of area estimates. There is a need to treat spatial and spectral data on an equal footing.

TABLE IV. CURRENT TECHNICAL ISSUES

- Training Selection and Labeling
(Ground Truth vs Imagery alone, Imagery with aids, Global or Universal Training)
- Sampling Schemes (Spatial and Temporal)
- Classification and Mensuration
 - Level of Detail at Which Reliable Discrimination Can Be Performed (e.g., Spring Wheat vs Spring Small Grains)
 - Prediction of Error Rates and
 - Use of Spatial and Spectral Data on an Equal Footing
- Use of Satellite Indicators to Supplement Predications
 - Combined Use of Metsat and Landsat Data
 - Use of Moisture in Yield Models
- Small Scale (Field) Structures
- Physical Factors (Atmospheric Modeling, Background Albedo Correction)
- Ancillary Data
- Geometric Quality (Within, say, 1/2 a pixel)
- Cost of Processing

Other technical issues concern the extent to which indicators derived from satellite observations can be used to supplement yield predictions, understanding the problem of small field structures, and the degree to which data variability due to atmospheric conditions/background albedo can be overcome by modeling.

A critical issue today concerns the proper role of ancillary data. Use of such data can improve reliability, but care must be taken not to place unrealistic demands on the sources of such data.

There is a concern that output products be geometrically correct within the limits of the Landsat system, and the issue of how to reduce the resources required to process a sufficient amount of data to yield significant conclusions is still with us.

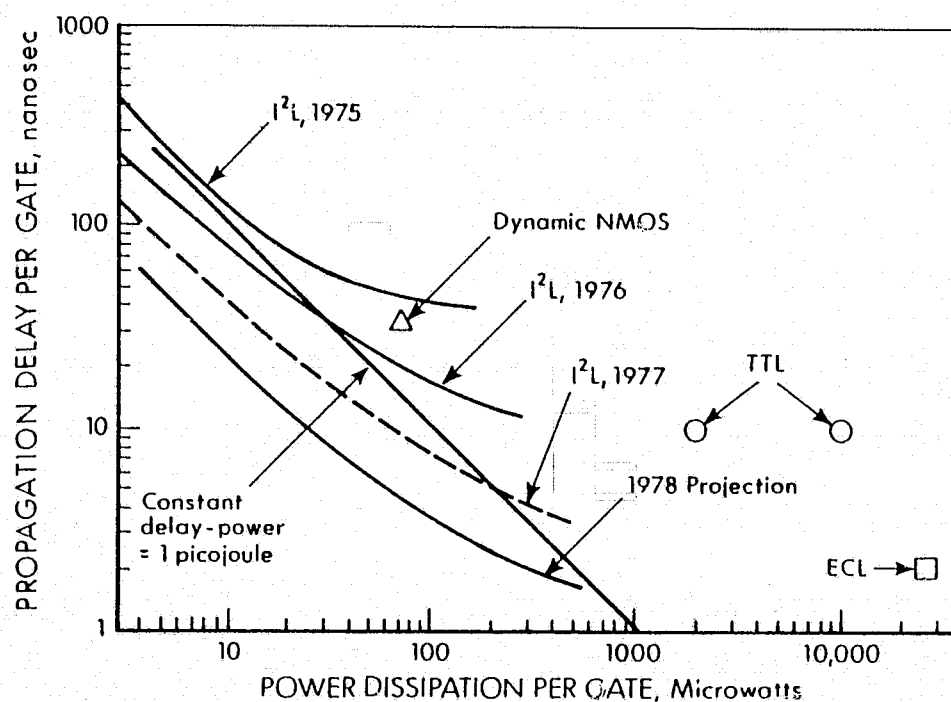
In large measure, the applicability of remote sensing to operational systems will be determined by the extent to which these technical issues are addressed.

4. WHERE MIGHT WE BE IN 1979?

The hardware technology which underpins digital computing is in a period of rapid evolution. In trying to forecast where remote sensing data analysis will be in early 1979 it is necessary to make some predictions concerning the corresponding developments in hardware technology. It is convenient to make these predictions separately in terms of memory hardware and for logical hardware. In

both areas an uncertainty enters due to the broad variety of technical approaches and the discrepancy between performance which can be demonstrated on a research oriented feasibility study and the performance which can actually be guaranteed in an application. Figure 1 shows a recent prediction for the growth of Bipolar Technology in terms of the propagation delay and power dissipation per gate. Using Integrated Injection Logic (I^2L) gate times ~ 1.5 nanosecond at 0.2 milliwatt should be achieved by 1979.

FIGURE 1.
EVOLUTION OF BIPOLAR TECHNOLOGY*



*Christiansen, Donald, Ed., "Technology '77"
IEEE Spectrum, January 1977

A way in which these gate delay times can be related to processing times is to consider that a typical arithmetic ADD instruction can be thought of as involving about 20 gate delays plus two random memory accesses and a typical MULTIPLY instruction involves about 120 gate delays plus two random memory accesses. One of the design tradeoffs which is available to the circuit designer is to permit additional power consumption in order to achieve increased speed. At least one hardware classifier has already been constructed using TTL logic wherein the basic clock rate is only 1/2 the time shown for TTL in Figure 1.

Corresponding projections of memory hardware for the late 1978 time frame are given in Table V. Again, the variety of technical approaches employed leaves one unsure as to whether these predictions are optimistic or pessimistic in terms of an actual application. However, a recent advertisement by MOSSTEK Corporation

indicates that 16K Random Access Memorys with 150 nanosecond access times will soon be on the market.

TABLE V. HARDWARE PROJECTIONS (MEMORY)

<u>RAM [ROM]</u>		<u>SLOW</u>	<u>FAST</u>
TECHNOLOGY	Semiconductor (16K)	N-Channel Silicon gate MOS	Bipolar Schottky
ACCESS TIME (nsec)	100 [100]	200	40
POWER DISSIPATION (mW/ 16K)	800 [400]	800	6400
DENSITY (bits/ cm ³)	3900 [3900]	<3x10 ⁶ >2x10 ³	<2x10 ⁵ >152
<u>SERIAL ACCESS</u>			
TECHNOLOGY	Semiconductor (65K)	----	----
SERIAL DATA RATE (MHz)	2-20	----	----
POWER DISSIPATION (mW/ 65K)	200	----	----
DENSITY (bits/cm ³)	3900	----	----

In summary, it seems reasonable to predict (See Table VI) serial instruction throughout rates of from $4-8 \times 10^6$ instructions/second in the early 1979 time frame. Wisely used, this increased speed can be of great benefit to the user of information extracted from remotely sensed data.

TABLE VI. PROJECTED CMOS GATE LEVEL AND MEMORY PARAMETERS IN EARLY 1979

<u>CATEGORY</u>	<u>PARAMETER</u>	<u>SPECIFICATION</u>
Logic Gates	Gate Delay	1.5 nsec
	Power Delay Product	0.5 picojoule
	Gate Power	0.2 mW
	Density	100 gates/mm ²
Random Access Memory	Access Time	40 nsec
	Power Dissipation (16K)	800 mW
	Density	4×10^3 bits/cm ³
Serial Access Memory	Data Rate	3 MHz
	Power Dissipation (65K)	200 mW
	Density	4×10^3 bits/cm ³

Pattern recognition is more than mathematical algorithms and the hardware/software environment in which these algorithms are embedded.

Recognition systems in 1979 will continue to require human interaction. The advent of higher spatial resolution satellites with much higher data rates will

necessitate a complete restructuring of our approach to remote sensing analysis. With more of the information content of these new images in the spatial properties of the images, more spatial processing will lead to more parallel processing systems based on array processors. Digital outputs from today's systems are grid-oriented image files. In 1979 we predict that the outputs will be imagery that are geometrically corrected to a Universal Transverse Mercator (UTM) grid with East-West oriented scan lines. Software for converting such outputs to the polygon structures of many North American resource data bases will be in place. Remote sensing systems will be drawing from these historical data bases features to improve a priori probability estimation and classification accuracies. In 1979 we anticipate that resource managers will have accepted the place of remote sensing as one of the important components in resource management and information systems, as opposed to the current desire of some remote sensing adherents to see remote sensing replace entirely existing systems for information collection.

1977 is a year in which no less than 14 Application System Verification and Test projects are being conducted wherein potential users remotely sensed information are helping explore how such information can be effectively employed. Between the increased understanding of their own discipline which each user group contributes, the advances in remote sensing techniques which will come from widespread experience with accurately registered multitemporal data taken over large areas, increased ability to model (or at least minimize) the effects of external factors, the whole realm of associative processing which is opening up in terms of shape and texture, and the underlying growth in hardware technology it is reasonable to predict that remote sensing analysis has the ability to overcome many of its current limitations and accomplish its true purpose. To us that purpose is to provide timely and accurate information from an extensive area at a cost that is worth paying.

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Currently there is considerable interest in active microwave sensors for earth resources applications. A particular example is the SEASAT-A radar. However, to obtain spatial resolutions comparable to optical sensors at radar frequencies, sophisticated image formation processing techniques must be applied to the raw data.

This paper briefly compares processing requirements for non-coherent optical and coherent radar imaging systems, and then discusses the image formation processing requirements for synthetic aperture radar (SAR) systems. Both optical and digital techniques are addressed, and examples of hardware and imagery for each processing technique are presented.

A major portion of the data currently used for earth resources applications is obtained from passive infrared and visible-region sensors. Many sophisticated signal processing techniques have been applied to multispectral scanner (MSS) data for the purposes of automatic classification or interpretation. However, prior to information extraction, the sensor data is in reasonably readable form, as a line-scan image intensity, and any required signal processing techniques are generally limited to geometric and radiometric corrections. In particular, the spatial resolution of the data, as determined by sensor optics and scan rates, is not significantly changed by processing. Typical spatial resolution of MSS systems from orbital altitudes is of the order of $50 \text{ m} \times 50 \text{ m}$.

Currently, there is considerable interest in active microwave sensors for earth resources applications [1]. A particularly important application is Side-Looking Airborne Radar (SLAR). Depending on altitude (or range) and wavelength, the degree of data processing required to generate a useful image may be minimal, for a real aperture radar such as the AN/APS-94 or AN/APQ-97; or extremely sophisticated, as for example, the planned SEASAT-A synthetic aperture radar.

Real aperture radar systems act in a similar manner as multispectral scanners in that angular spatial resolution is determined by the ratio of wavelength to antenna aperture size, and the resulting video signal can be displayed without additional processing. However, such systems are generally useful

only at short wavelengths and relatively short range. Synthetic Aperture Radar (SAR) systems are able to bypass the above resolution limit by using the forward motion of the sensor to synthesize, in effect, an aperture many times longer than the actual antenna. The image-formation processing required for SAR systems may require orders of magnitude more high speed memory capacity and higher arithmetic rates than typical MSS image processing.

2

NON-COHERENT AND COHERENT IMAGING SYSTEM COMPARISON

In comparing the processing requirements of non-coherent and coherent imaging systems, it is useful to first compare the nature of the unprocessed and processed images. First consider a typical non-coherent imaging system, such as an airborne optical scanning system. A raw scanner output image is shown in Figure 1(a), and a rectified image is shown in Figure 1(b). Note that the raw image, though distorted, is recognizable, and can easily be exploited by a trained interpreter.

Now consider a typical coherent imaging system such as an SAR. A magnified image of the raw radar video, which has been recorded with a sufficiently high offset carrier frequency to preserve both phase and amplitude is shown in Figure 2(a). A typical processed image is shown in Figure 2(b). Note that the unprocessed image is essentially unintelligible. This is because the unprocessed resolution of the radar, determined by transmitted pulse length and real antenna beamwidth, is insufficient to resolve objects in the illuminated scene; i.e., individual target returns are dispersed and overlapping throughout the unprocessed image. The fine structure observed in Figure 2(a) is due to the combined phase modulation of the returned radar signal due to the targets in the scene. The only interpretable part of this image is a portion of a Fresnel zone plate which indicates the presence of a strong, isolated point reflector.

Now, because the coherent radar imaging processes is fundamentally linear, and the amplitude and phase modulation of an individual signal can be predicted from knowledge of the transmitted pulse and system geometry, it is possible, for each point in the image, to construct a matched filter which will compress the two-dimensional dispersed signal to one of much finer resolution, yielding an image such as shown in Figure 2(b).

The relation between unprocessed and processed, or compressed, resolution cell size is illustrated in Figure 3 in which we show the raw system ground resolution, determined by the pulse length and the azimuth beamwidth; and show by comparison, the final system resolution defined by the compressed pulse length and the azimuth resolution of the synthetic aperture. Depending on system parameters, the range and azimuth compression ratios may vary from less than one hundred to several thousand.

After compression, or image formation, additional amplitude and geometric corrections may be required before image exploitation. These may include, for example, compensation for the antenna gain pattern and slant range to ground range conversion.

A simplified functional block diagram comparing non-coherent and coherent imaging systems is shown in Figure 4. Note that the principal difference is the insertion of an image formation processor in the coherent imaging system. The principles and history of SAR image formation processors will be presented in the balance of this paper.

3

SAR PROCESSING REQUIREMENTS

Let us first quantify SAR image formation processing requirements. The real aperture azimuth resolution of an imaging radar is bounded by

$$\rho_a \geq R(\lambda/d_a) \quad (1)$$

where R = slant range
 λ = radar wavelength, and
 d_a = azimuth aperture length.

Resolution as a function of range and aperture length in wavelengths is shown in Figure 5. If we assume a maximum diffraction limited aperture of 1000 wavelengths, then resolution at aircraft ranges of 50 km or less is acceptable for some earth resource applications. However, at orbital altitudes, the best resolution is of the order of 1 km, and, may be of little value. In addition, for aircraft or satellite applications, physical apertures of this length would be practical only at wavelengths of 1 cm or less. Hence, real aperture radars are generally useful only at short range or short wavelengths.

By coherently recording and then processing the radar returns from several successive pulses, a synthetic aperture of length L_A can be generated with a resulting azimuth resolution limit of

$$\rho_a \geq \frac{R\lambda}{2L_A} \quad (2)$$

□

The limiting synthetic aperture length is equal to the real aperture resolution of $R(\lambda/d_a)$. Substituting this in Eq. 2 gives the lower bound on azimuth resolution of

$$\rho_a \geq \frac{d_a}{2} \quad (3)$$

which is independent of range and wavelength. A system attaining this limiting resolution is termed a fully focussed SAR. In many cases, requirements or system phase errors may limit the required or attainable synthetic aperture length to less than the antenna azimuth footprint size, in which case coarser azimuth resolution is attained.

A measure of the azimuth processing complexity is the azimuth processor compression ratio which is given by

$$C_A = \frac{L_A}{\rho_a} = \frac{R\lambda}{2\rho_a} \quad (4)$$

Note that C_A is proportional to range and wavelength, but most importantly, is inversely proportional to the square of azimuth resolution. Typical SAR azimuth compression ratios vary from 10 to 200.

A second measure of complexity is the beam-sharpening ratio which is the ratio of real aperture resolution to synthetic aperture resolution, given by

$$B_A = \frac{R\lambda}{d_a \rho_a} \quad (5)$$

In particular, $C_A \leq B_A$, the limiting case being a fully focused SAR.

In general a SAR system also requires range compression. This is because average power is proportional to pulse width. If the transmitted pulse was made sufficiently short to achieve the required range resolution, the average transmitted power (assuming a peak power limited transmitter) would be insufficient to achieve an adequate signal-to-noise ratio. Hence, conventional radar pulse compression techniques are used, in which a sufficiently long phase modulated pulse is transmitted. The resolution of the compressed pulse is inversely proportional to the transmitted bandwidth, B . Hence the achievable ground range

resolution is given by

$$\rho_g = \frac{c}{2B} \csc \phi \quad (6)$$

where c = velocity of propagation,
 B = radar bandwidth, and
 ϕ = incidence angle.

The range compression ratio is given by the pulse time-bandwidth product,

$$C_R = TB \quad (7)$$

where T = transmitted pulse length.

Typical pulse compression ratios for SAR vary from 30 to 600.

4 NON-COHERENT INTEGRATION

The previous section addressed SAR coherent processing requirements. In many cases, system errors, or processing cost, limit azimuth resolution to several times the theoretical limit. In this case, it is possible to separately process the remaining portions of the total available aperture and then non-coherently sum the resulting images. This results in an image of the same resolution, but having significantly reduced speckle. In a similar manner, excess range bandwidth can be transmitted, and the resulting signals separately processed to obtain statistically uncorrelated images which can be non-coherently combined to reduce the speckle associated with single-look coherent images [2].

The first technique is referred to as the use of angle diversity since it uses different portions of the angular azimuth beamwidth to obtain the separate looks. The second technique is termed frequency diversity since separate transmitted frequency bands are used. This combined processing is generally termed mixed integration or multiple-look SAR processing. Examples of 1, 4 and 16-look processing of an orchard at 6×6 meter resolution is shown in Figures 6(a) through 6(c). Note the improvement in image interpretability due to the smoothing or speckle reduction obtained by mixed integration. Figure 6(d) shows the same scene in which the available data has been completely coherently processed to a resolution of 1.5×2.1 meters. This image has the same speckle amplitude statistics as Figure 6(a), but the speckle area has been reduced by more than a factor of 10, and hence is less objectionable to the observer. In addition, the finer resolution of Figure 6(d) results in a higher information content, and generally more useful image. The conclusion is that the image formation processor should be designed to achieve the finest possible resolution consistent with system phase errors and processing cost. Then, any additional bandwidth or azimuth beamwidth should be used for mixed integration processing to reduce image speckle.

Functional diagrams of mixed integration processing using angle diversity and frequency diversity are shown in Figures 7(a) and 7(b). Figure 7(b) shows that similar multiple processors are used to obtain the separate images which are then non-coherently combined.

5 SAR IMAGE-FORMATION PROCESSING TECHNIQUES

From the previous sections, we observe that SAR image formation processing consists of the following principal steps: (1) signal recording, (2) range/azimuth correlation, (3) non-coherent integration and (4) display. The principal technologies applied to SAR processing have been (1) electronic, (2) optical, (3) digital, and (4) hybrid techniques. Analog electronic techniques were initially used to demonstrate that resolution finer than the real aperture beamwidth

could be obtained by Doppler signal filtering. However, these processors did not have the capability of achieving the aperture limiting resolution of a fully focused SAR.

Fortunately, early in the development of SAR techniques, it was recognized that a coherently illuminated optical channel was well matched to the two-dimensional processing of suitably recorded SAR signals [3]. In fact, most of the SAR images available for earth resources applications have been optically processed. However, digital techniques are now being introduced, with certain advantages, in SAR image-formation processing applications.

If brute force digital techniques were used for SAR image-formation processing, several thousand multiplications and additions might be required for each image pixel generated. The use of efficient signal processing algorithms such as the Fast Fourier Transform (FFT) can reduce this computational load by orders of magnitude, thus making digital processing feasible. However, computer memory requirements are enormous. A typical SAR digital processor may require a memory size of several hundred megabits. It is only recently, due to rapid advances in integrated circuit technology, that real-time, or near-real time, digital processing of large-scene fine-resolution radar images has become technically and economically feasible.

5.1 OPTICAL PROCESSING

A block diagram of a typical SAR system using coherent optical processing is shown in Figure 8. Data is recorded on photographic film, either on-board the radar vehicle, or on the ground via a wideband data link. The developed signal film is placed in an optical correlator and the correlator output image is recorded on film. An image digitizer may also be included as part of the correlator in order to generate data for further image processing by a digital computer.

Details of the recording geometry are shown in Figure 9. Figure 10 shows the resulting signal history of a single point target as recorded on film. The change in slant range is exaggerated in this figure to show that the range to the target changes during the recording of the data in a synthetic aperture. If this change in range (range curvature) is excessive, additional special processing techniques are required. Figure 10 assumes a linear FM (chirp) wave form is transmitted for range pulse compression. The resulting signal is then equivalent to a distorted Fresnel zone plate which has certain self-focusing properties which make optical processing feasible.

Figure 11 is a diagram of a tilted-plane optical correlator [4] which would be used to process the signal film of Figure 10. The tilt angles of the input and output film, and the arrangement of spherical and cylindrical lenses are required to compensate for the fact that the focal properties of the signal film are different in the range and azimuth directions, and that the azimuth focus varies with range. This processor configuration is also capable of performing mixed integration processing of SAR data. Its conception and demonstration at The University of Michigan in the early 1960's was a significant milestone in SAR image-formation processing technology.

5.2 DIGITAL PROCESSING

A block diagram of a typical SAR system using digital processing techniques is shown in Figure 12. In this case, the signals are digitized, buffered and then stored on high-density magnetic tape. The tape recorders are usually 14 or 28-track instrumentation recorders recording digital data at a density of 20,000 bits per inch (50,800 bits per cm) per track. The data is then played back at real time or slowed down by factors of 32:1 to 128:1 for processing.

A functional diagram of a possible digital processor configuration for the SEASAT-A radar is shown in Figure 13. The digitally recorded data is played back and put in the proper format for computer processing. If the along-track or azimuth sampling rate introduced by the radar pulse repetition frequency (PRF) is much higher than one sample per azimuth resolution cell spacing; or if angle diversity is being used, the data may be prefiltered or presumed in azimuth to reduce the processor data rate and memory requirement.

Range compression is typically done first, although, in some cases, it is advantageous to do it after azimuth compression. The data is then stored in the azimuth memory. The azimuth memory size is determined by the number of range samples times the azimuth compression ratio times the number of looks. If angle diversity is used, an additional large memory is needed to store the processed data before non-coherent integration. This total memory represents one of the major investments in a digital SAR image formation processor. Actual memory requirements depend somewhat on the processing algorithm used, but a nominal size is given by the following expression

$$M_A = \frac{W}{\rho_g} \cdot \frac{R\lambda}{2\rho_a} \cdot (N_R N_A + N_A - 1) \cdot 2q \quad (8)$$

where W is the ground-range swath; ρ_g is the ground-range resolution; N_R is the number of range looks (frequency diversity factor) and N_A is the number of azimuth looks (angle diversity factor); q is the average word size; and other terms have been previously defined. The first term in Eq. 8 is the number of range samples, the second term is the azimuth compression ratio, the third expression is the additional memory needed for non-coherent integration, and the last term represents the word size and a factor of two to satisfy the usual Nyquist sampling criterion. Quantization requirements before compression are modest. Typically three to six bits are adequate because of the dispersed nature of the data. After compression 8 to 16 bits may be required if linear amplitude coding is used.

It is important to note that if range and azimuth resolution are the same, memory requirements are inversely proportional to the cube of resolution.

In principle, SAR image formation processing could be done on a general purpose digital computer. However, the arithmetic and data handling requirements make this a very slow and expensive approach for large images requiring large azimuth compression ratios. An important problem is the azimuth memory data storage which can be interpreted as a large two-dimensional array in which the range samples (returns from each sample pulse) are stored as rows, and the azimuth samples (for a fixed range) are stored as columns. The data is received by rows, and range compression can be done one row at a time. After range compression, the data must be accessed by columns. In most cases of interest, the total synthetic array data cannot be contained in high-speed memory, but must be partitioned into blocks or pages on auxiliary low-speed data storage (drums or disks). Therefore, considerable attention must be given to relatively slow input/output (I/O) data handling routines. In addition, the arithmetic rates of affordable general purpose computers are too slow to permit reasonable operational processing rates. Typical SAR image-formation processing times for useful scene sizes would be measured in hours or days depending on the particular computer configuration and radar parameters. Hence, general purpose computers are not a serious candidate for SAR image-formation processing for earth resources applications.

A second approach to digital processing is to configure a collection of special purpose high-speed signal processors, I/O devices, and high-speed memory under the control of a general-purpose minicomputer as shown in Figure 14. These special purpose processors are capable of performing array multiplications, Fast Fourier Transforms (FFT's), and similar signal processing operations with a single instruction. Arithmetic rates may be on the order of 10 to 20 million complex multiplications and additions per second. Coupled with an efficient memory management system, this configuration is considerably faster, more efficient, and generally cheaper than a general purpose computer system. However, such a system is generally unable to operate in real-time due to arithmetic and I/O data rate limitations. Typical I/O devices associated with this type of a processor would be high-density digital tape recorders operating at a data slow-down of the order of 32:1.

For real-time applications, special purpose hardwired computers are used for SAR digital image-formation processing. These units are designed to match the arithmetic and data flow requirements for SAR signals. A large degree of parallelism may be used to attain the required data rate.

Several programs sponsored by the U.S. Air Force and Navy have demonstrated the possibility of digital SAR image formation processing. The most ambitious program currently under development is the SAPPHIRE processor which will be discussed in a later section of this paper.

6 EXPLOITATION

Once an image has been obtained from the SAR image formation processor the usual techniques may be employed for exploitation.

The digital exploitation of optical scanner data has achieved a high degree of sophistication. To date, little work has been performed using digital processing techniques to exploit synthetic aperture radar data. SAR data due to its unique geometry and collection procedure creates special data processing problems [5].

Among the processes used on SAR data with success for feature enhancement are level slicing of single channel data, ratioing of two channels (X-L band and cross polarized), additive and subtractive combinations of multiple bands and various smoothing and classification algorithms. The processed SAR data can be displayed on black and white and color CRT computer terminals for operator interaction or can be produced as hard copy output using a color ink jet printer.

7 SEASAT-A IMAGE FORMATION PROCESSING REQUIREMENTS

The planned SEASAT-A radar will operate at a wavelength of 23 cm with an 11-meter antenna having a beamwidth of the order of 1 degree. The real aperture resolution on the ground at an altitude of 800 km is about 15 km. The radar will have a transmitted bandwidth of 19 MHz, pulse length of 33 μ sec, and a pulse repetition frequency (PRF) of 1463 to 1645 pulses per second. The raw data will be telemetered to the ground as an analog signal where it will be received, digitized to 5-bits at a rate of 45.5 megasamples per second and recorded on a high-density digital tape recorder for subsequent image formation processing.

The compressed signal resolution requirements are 7.9 m in slant range (25 m on the surface at a 20 degree incidence angle) and 25 m in azimuth. Angle diversity processing is to be used to generate the maximum capability of four azimuth looks. The required range and azimuth compression ratios are approximately 640 and 200, respectively, for each independent look.

The range swath is 100 km and the azimuth extent for each 10-minute pass is 4000 km. A total of 400 passes will be recorded. Of these, 260 will be processed into film strips and 26 of those will also be recorded on computer compatible tape as 100 $\times$ 100 km frames. The output images will be geometrically corrected (in ground range coordinates).

The desired processing time-lines are: (1) quick look of each pass within 48 hours, (2) film imagery within 10 days of recording, and (3) CCT imagery within 20 days of request.

The single-pass SEASAT-A image formation processing requirements are within the capabilities of current optical and digital processing technology. However, the proposed operational time-lines and output data handling requirements will place severe demands on the system. Optical processing has the advantages of lower cost and risk, a significant heritage and user experience. A digital processor has the advantage of increased flexibility in handling geometric corrections required during and after processing, attaining better control of the image impulse response side lobes, and amplitude calibration.

The final selection of a SEASAT-A image formation processing approach has not yet been made. However, based on cost-performance tradeoffs, it is likely to be a hybrid approach involving digital or electronic pre-processing, film recording, optical correlation, and both film and image digitization readout options.

SAR IMAGE FORMATION PROCESSOR TECHNOLOGY

This section gives a brief history of the synthetic aperture radar (SAR) processors developed and/or used at Goodyear Aerospace Corporation since 1952.

The first SAR processors were analog electronic devices using storage tubes for memory and one-pole RC or two-pole LC electronic filters as the processing elements. Resolutions attained, although a small fraction of the illuminated beamwidth, were 100 m or more. Later, optical data processors, more commonly referred to as correlators or correlator-processors, were conceived and demonstrated at the Willow Run Laboratory of The University of Michigan (now ERIM) and developed at Goodyear Aerospace Corporation for operational use. These transform holographic phase histories, which were recorded on airborne radar signal films, into radar images. For example, fully automatic correlator-processors have been designed and manufactured for such systems as the AN/APQ-102A and AN/UPD-4. Many of these devices, similar to the one shown in Figure 15 (ES-82A correlator-processor), have self-contained, automatic film processing systems, functionally described in Figure 16, that enable the rapid development, fixing, and drying of data and image films. Illuminated viewing tables permit the analysis of the final image film immediately after processing. This type of unit has been used with a wideband data link to provide real-time, near-real time processing and viewing of radar imagery. Film transport and chemical processing requirements necessitate approximately five minutes delay from radar illumination of an area to viewing the same area on the attached viewing table. Typical imagery from the AN/UPD-4 radar processed on the ES-83A correlators shown in Figure 17.

More versatile laboratory environment optical correlators have also been designed and manufactured by Goodyear Aerospace, patterned after the precision optical processor designed at The University of Michigan in the mid-1950's. One example is given in Figure 18 which shows the Universal Radar Signal Processor developed and built for the U.S. Army Engineers Topographic Laboratory, Fort Belvoir, Virginia. Various film sizes and formats (70 mm to 9 in) can be processed. It was truly a Universal radar signal processor because it could process radar data for any SAR in existence at the time (1968). In general, optics technology has not been a constraint on the capabilities of optical correlators. Film technology and film recording technology have usually been the determining factors for resolution, swath width, and dynamic range in optical correlators. Color film has been used at the output image plane to obtain greater dynamic range. Standard three-emulsion (three colors) film is used. Each emulsion has a sensitivity to the chosen monochromatic source different from that processed by the others. Improvements in capturing the dynamic range of optical correlators have recently been implemented at both the Environmental Research Institute of Michigan (ERIM) and Goodyear Aerospace Corporation. The improvement included an image dissector placed at the output image plane, analog-to-digital (A/D) conversion, and recording on computer-compatible magnetic tape.

Because of recent advances in integrated circuit technology, real-time digital processing of large scene, fine-resolution radar images has become technically and economically feasible. The most significant characteristics of real-time digital SAR processors are memory size and processing rate. Table I lists memory sizes in megabits and processing rates in millions of instructions per second (MIPS) for some recently developed real-time SAR digital processors. The table also includes some large scale, general purpose digital processors for comparison. The SEASAT processor parameters shown assume a real-time full swath, four-look azimuth processor. It should be noted that the real-time four-look SEASAT processor is similar in memory requirements and processing rates to SAPPHIRE*, a digital processor developed for the U.S. Air Force as a major element of Phase 1 of the AN/UPD-X advanced reconnaissance radar program. The purpose of SAPPHIRE is to demonstrate the practicality of building, operating, and maintaining a large capacity, hardwired, high performance digital processor SAR and to provide the means for experimenting with a wide range of performance parameters to establish the optimum configuration of an operational system. SAPPHIRE provides

*Synthetic Aperture Precision Processor High Reliability.

1-3

TABLE I. DIGITAL PROCESSOR TECHNOLOGY

	MEMORY SIZE (MBITS)	MIPS	TECHNOLOGY DATE
SAPPHIRE	35	4,300	1974
RAPID	6	150	1976
HIRSADAP	3.5	1,000	1971
STARAN	9.6	64	1970
ILLIAC-4	24 8	1,000 15	1966 OBJECTIVE ACCOMPLISHMENT
SEASAT-A	44	15,000	1978?

an 18.5 km (10 nmi) swath width with better than 3-m resolution in both range and azimuth, with -30-dB side lobes, more than 50-dB dynamic range, and a high tolerance for aircraft motions. It has provisions for resolution/multiple-look tradeoff studies, for color encoded display studies, and for interfacing with a real-time change detector. A sample of SAPPHIRE imagery is shown in Figure 19. The SAPPHIRE equipment is divided into airborne and ground-based subsystems. The airborne system includes a pre-processor which reduces the radar data rates to only that required for the final image, a 28-channel high-density tape recorder for recording that data, and a control console. Associated with this equipment is a modified AN/APD-10 side-looking radar system and an LTN-51 inertial navigation system. Provisions are also made for a future data link which could replace the tape recorder. The ground subsystem includes both range and azimuth processors with the required wide range of tradeoff capability, a display system using both black and white and color encoded CRT monitors, a digital data tape playback recorder, a digital tape image recorder, and a laser beam recorder for hard-copy imaging. The airborne subsystem of SAPPHIRE is currently installed in a C-141 aircraft. The ground-based equipment layout is shown in Figure 20.

Table II shows another comparison of large scale, real-time digital SAR processors. The SEASAT-A real-time processor is also shown for comparison. A measure of complexity or quality of SAR correlators or processors may be defined by the product of number of resolution elements across the swath, range compression, azimuth compression, number of processing channels (number of looks for a digital processor), i.e.,

$$QF = \frac{W}{\rho} \cdot C_R \cdot C_A \cdot N_L \quad (9)$$

The SEASAT-A processor quality factor would then be

$$QF = 4000 \cdot 640 \cdot 200 \cdot 4 = 2 \cdot 10^9$$

The quality factor for various optical processors developed over the past several years is shown in Figure 21. Also shown for comparison are the SAPPHIRE and SEASAT processors. It should be noted that the SEASAT quality factor requirements are equivalent to the most advanced optical or digital SAR processors in existence today.

TABLE II. SAR DIGITAL PROCESSOR PARAMETERS

	RANGE SWATH (PIXELS)	RANGE COMPRESSION	AZIMUTH COMPRESSION	MEMORY SIZE (MBITS)
SAPPHIRE	12,000	144:1	296:1	35
RAPID	2,000	16:1	64:1	6.2
HIRSADAP	3,000	100:1	96:1	3.5
SEASAT-A	4,000	640:1	200:1	44

9

SUMMARY

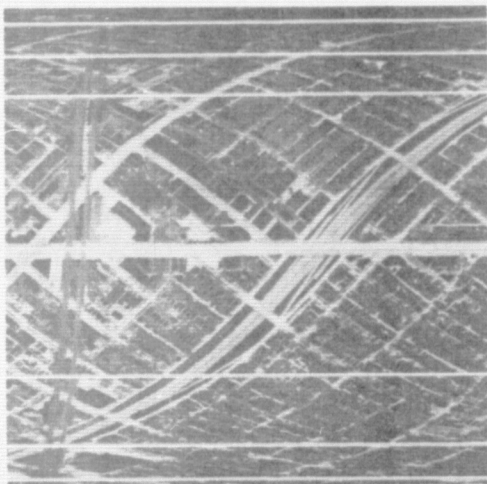
Fine resolution coherent microwave imaging systems generally require sophisticated image formation processing techniques before image exploitation techniques can be applied. Some of the requirements and present technology have been reviewed in this paper. Additional material and references on SAR image formation technology can be found in [6].

10

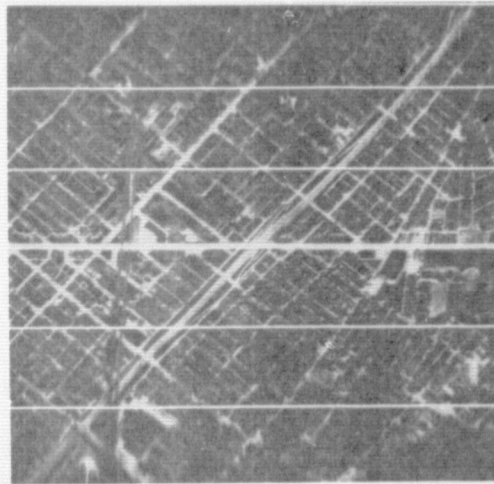
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2. Leonard J. Porcello, Norman G. Massey, Richard B. Innes, and James M. Marks, "Speckle Reduction in Synthetic Aperture Radars," J. Opt. Soc. Am., 66, pp. 1305-1311, 1976.
3. L.J. Cutrona, E.N. Leith, L.J. Porcello, and W.E. Vivian, "On the Application of Coherent Optical Processing Techniques to Synthetic Aperture Radar," Proc. IEEE, 54, pp. 1026-1032 (1966).
4. A. Kozma, E.N. Leith, and N.G. Massey, "Tilted-Plane Optical Processor," Appl. Opt., 11, pp. 1766-1777 (1972).
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6. John J. Kovaly, Ed., Synthetic Aperture Radar, Artech House, Inc., Dedham, Mass., (1976)

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(a) Uncorrected

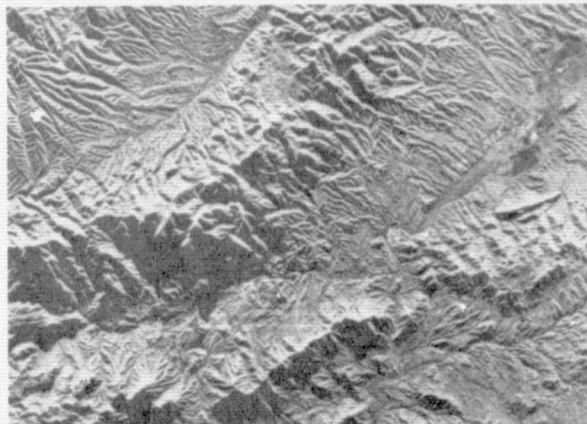


(b) Corrected

FIGURE 1. OPTICAL SCANNER IMAGE



(a) Unprocessed Data



(b) Processed Image

FIGURE 2. SAR DATA

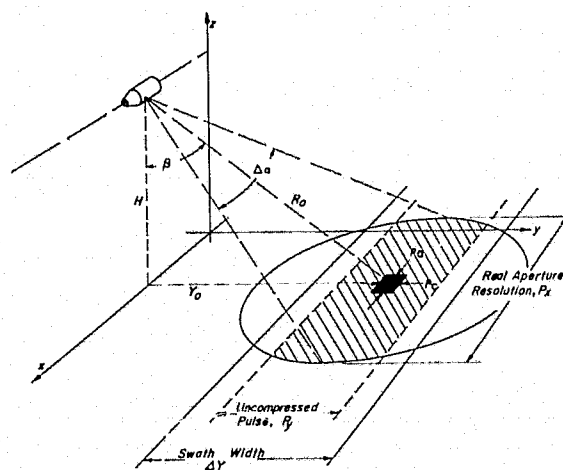


FIGURE 3. SAR FOOTPRINT

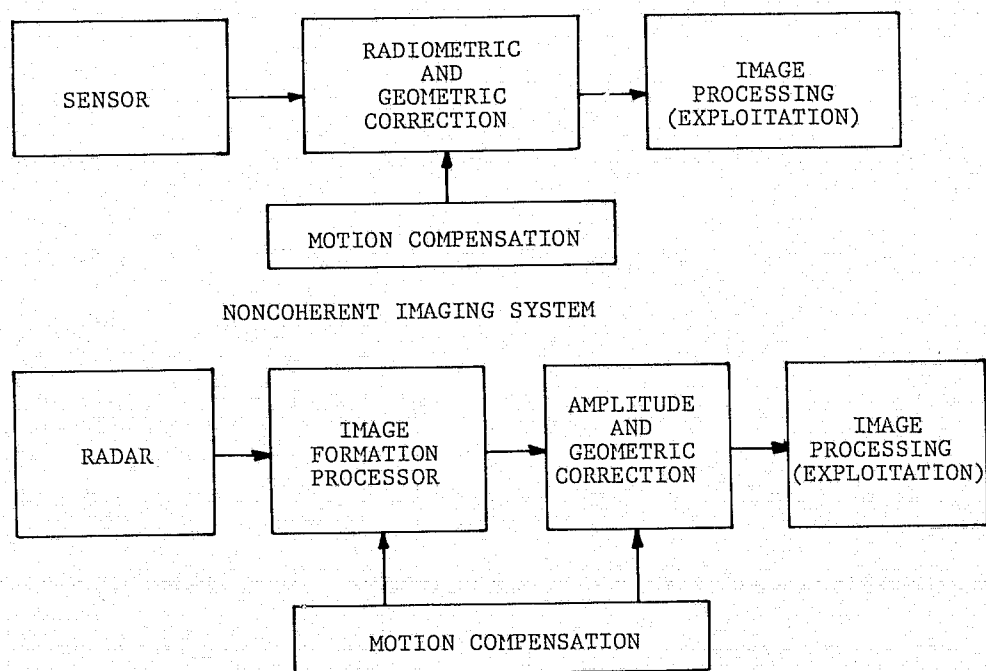


FIGURE 4. IMAGING SYSTEM COMPARISON

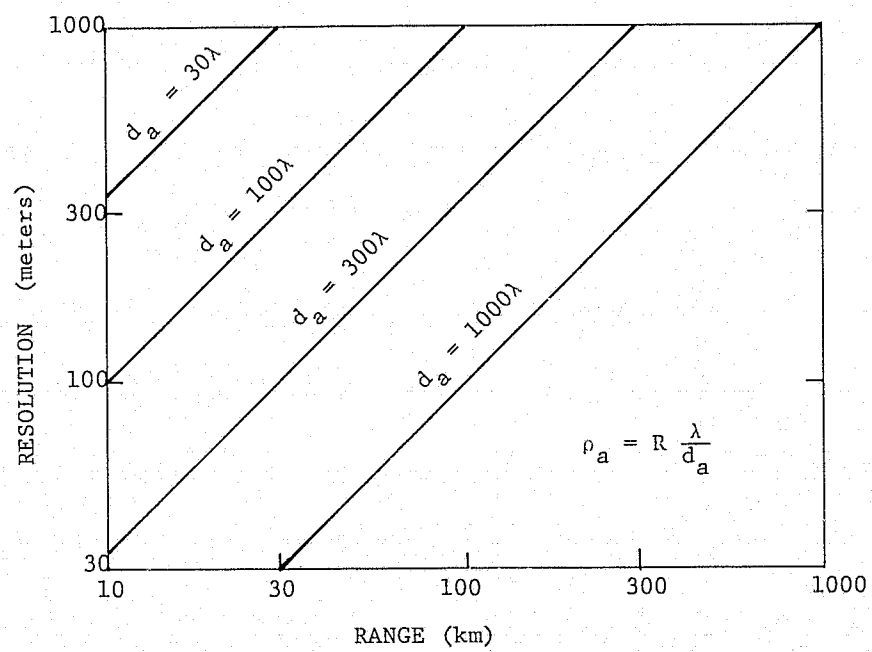
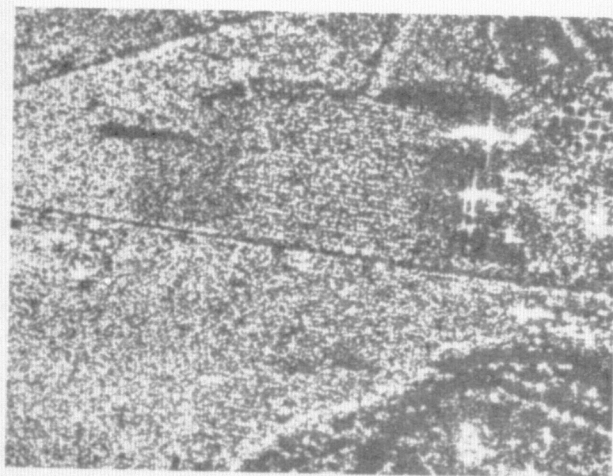
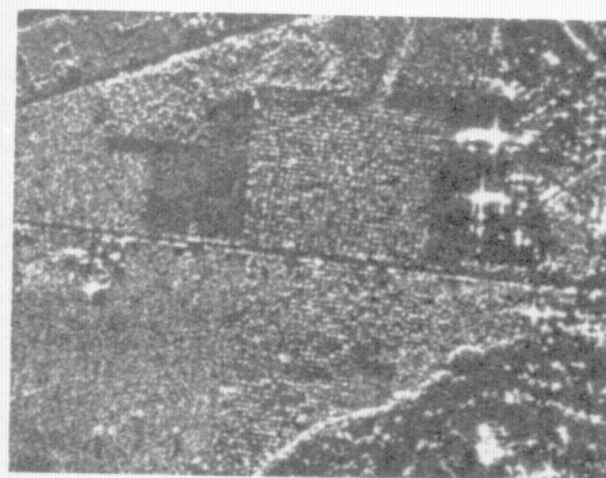


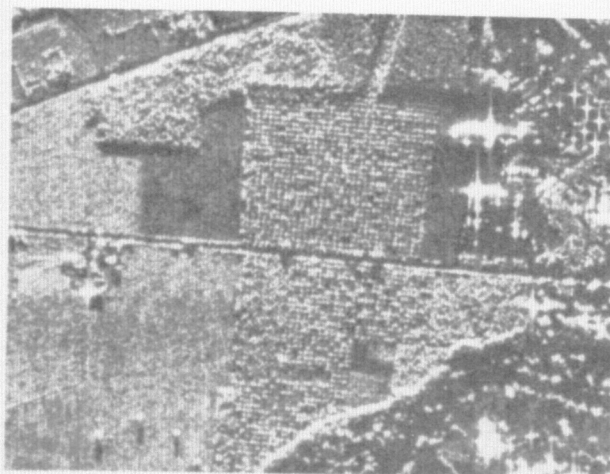
FIGURE 5. REAL APERTURE RADAR RESOLUTION



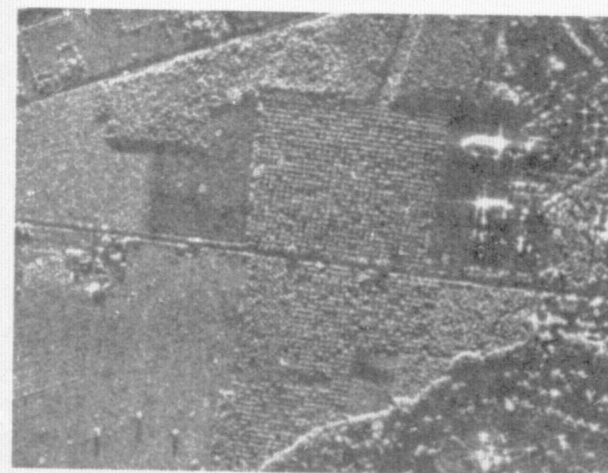
(a) 6×6 m, 1-Look



(b) 6×6 m, 4-Look



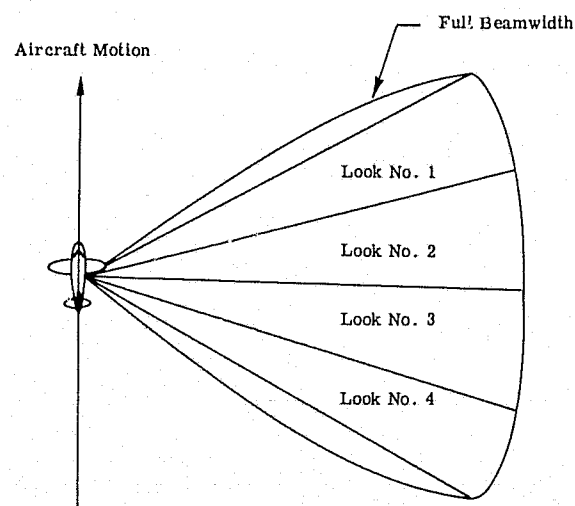
(c) 6×6 m, 16-Look



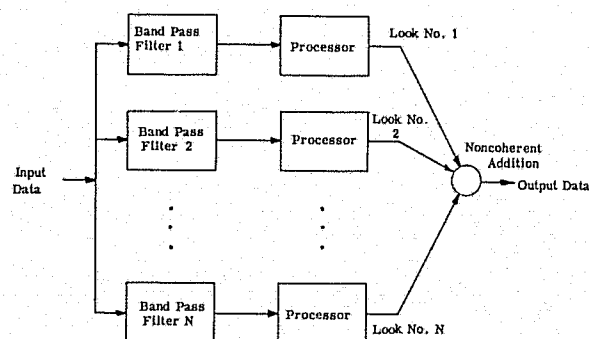
(d) 1.5×2.1 m, 1-Look

FIGURE 6. IMAGERY SHOWING EFFECT OF MIXED INTEGRATION AND FINER RESOLUTION

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(a) Angle Diversity



(b) Frequency Diversity

FIGURE 7. FUNCTIONAL DIAGRAM OF SAR DIVERSITY TECHNIQUES

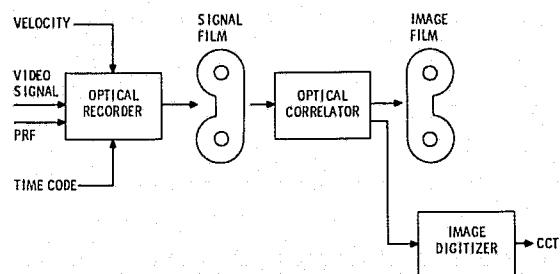


FIGURE 8. SAR OPTICAL PROCESSING BLOCK DIAGRAM

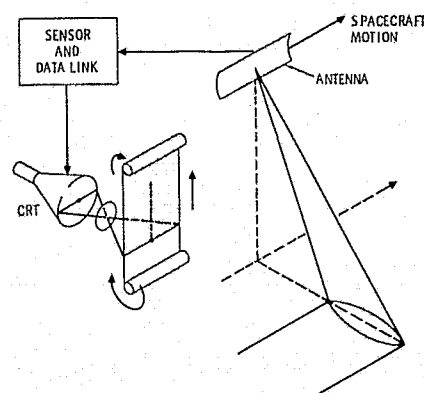


FIGURE 9. RECORDING GEOMETRY

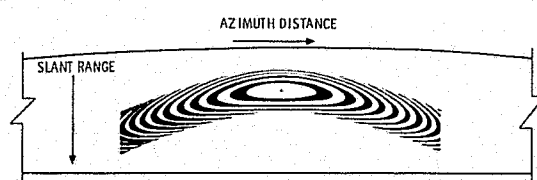


FIGURE 10. RECORDED SIGNAL HISTORY

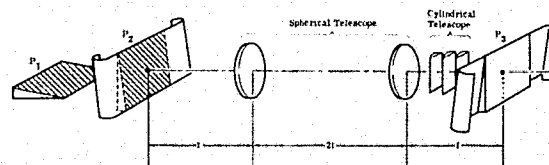


FIGURE 11. OPTICAL CORRELATOR

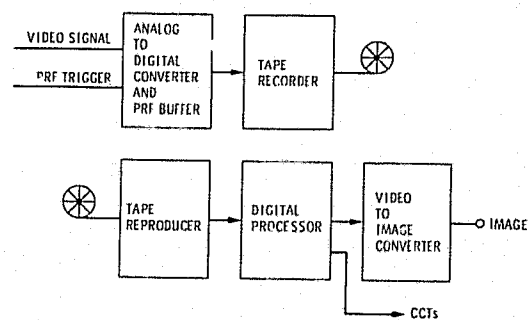


FIGURE 12. SAR DIGITAL PROCESSING SYSTEM BLOCK DIAGRAM

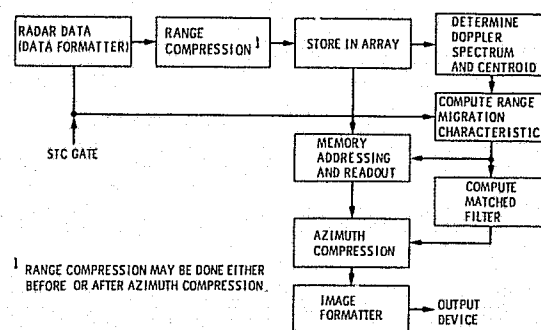


FIGURE 13. DIGITAL PROCESSOR FUNCTIONAL DIAGRAM

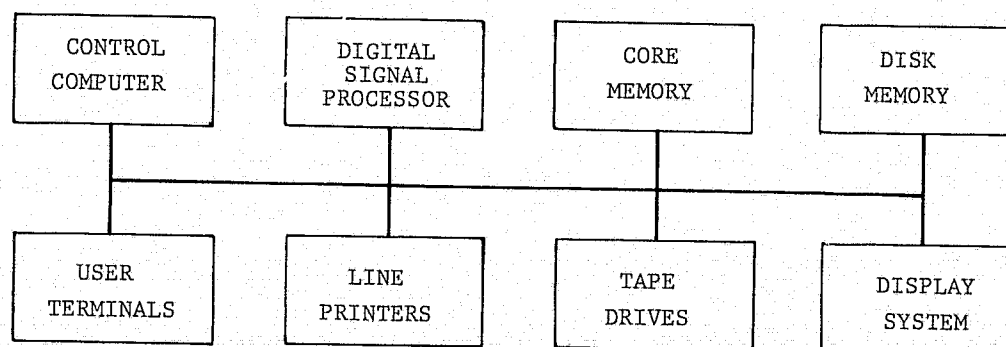


FIGURE 14. SAR DIGITAL PROCESSING USING A HIGH-SPEED SIGNAL PROCESSOR

ORIGINAL PAGE IS
OF POOR QUALITY

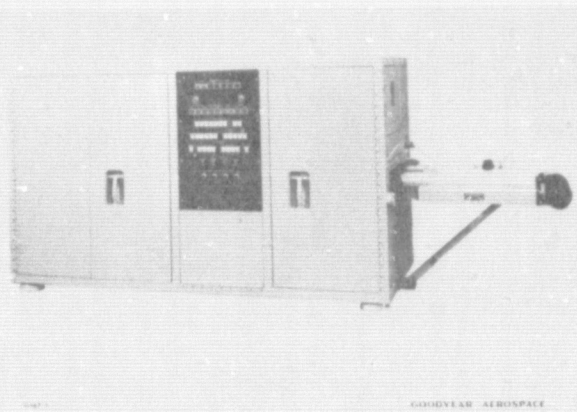


FIGURE 15. ES-83A CORRELATOR PROCESSOR

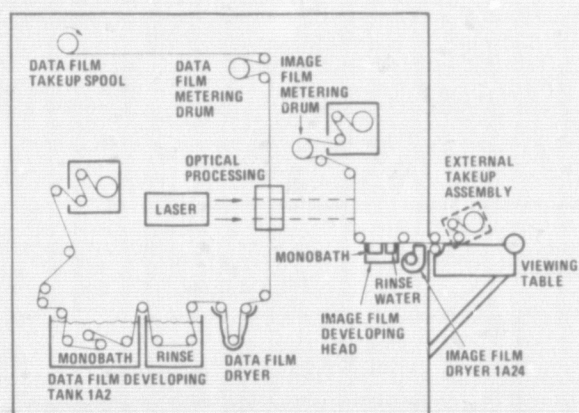
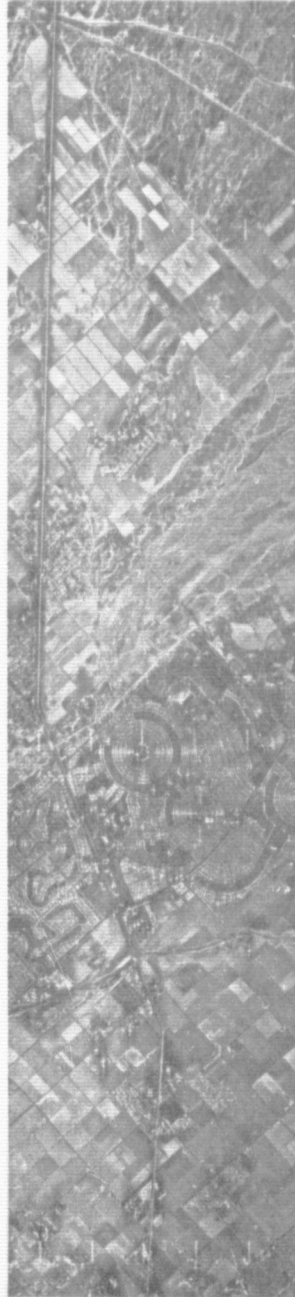


FIGURE 16. ES-83A FUNCTIONAL DIAGRAM

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Farmland



Sun City



Phoenix

FIGURE 17. AN/UPD-4 IMAGERY

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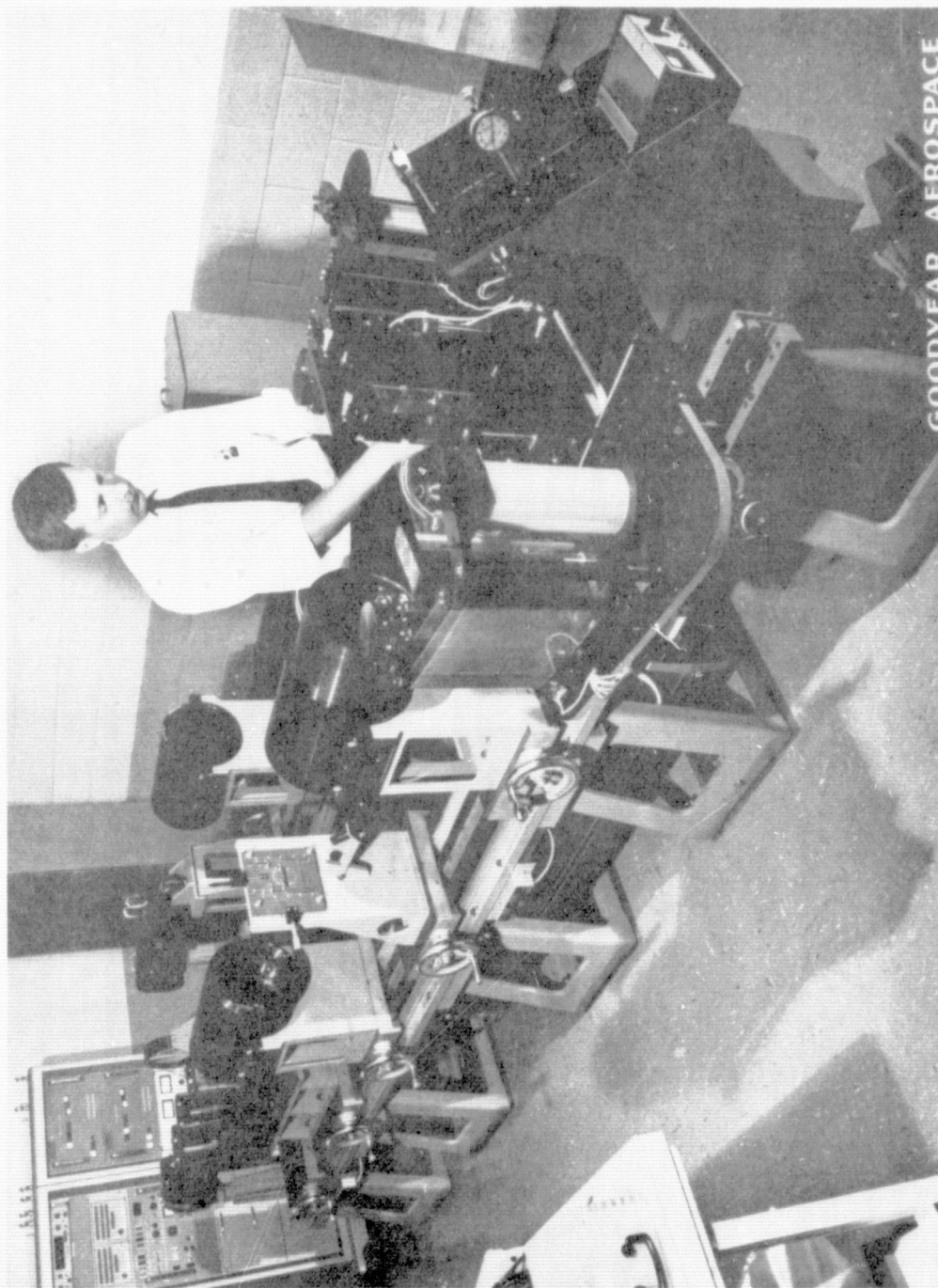
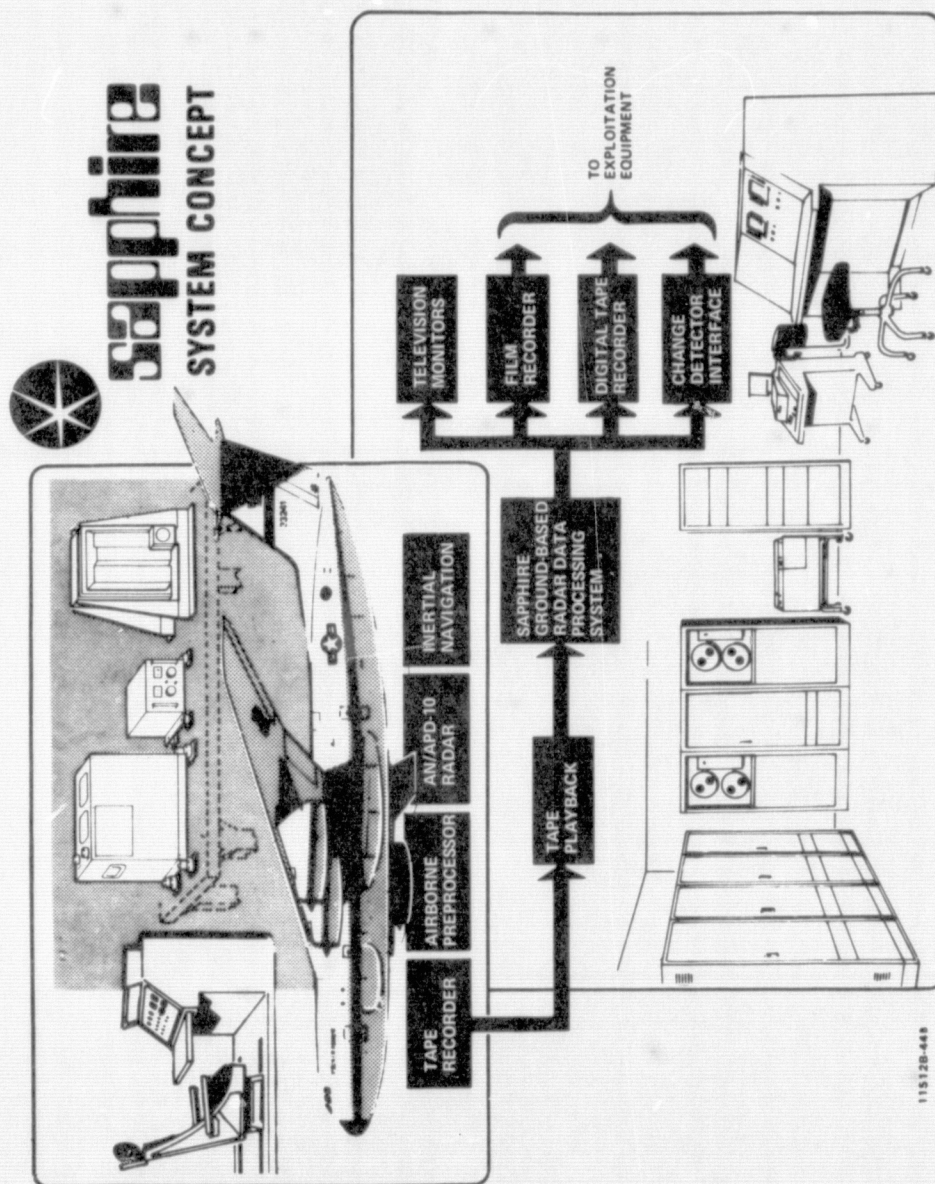


FIGURE 18. UNIVERSAL RADAR SIGNAL PROCESSOR

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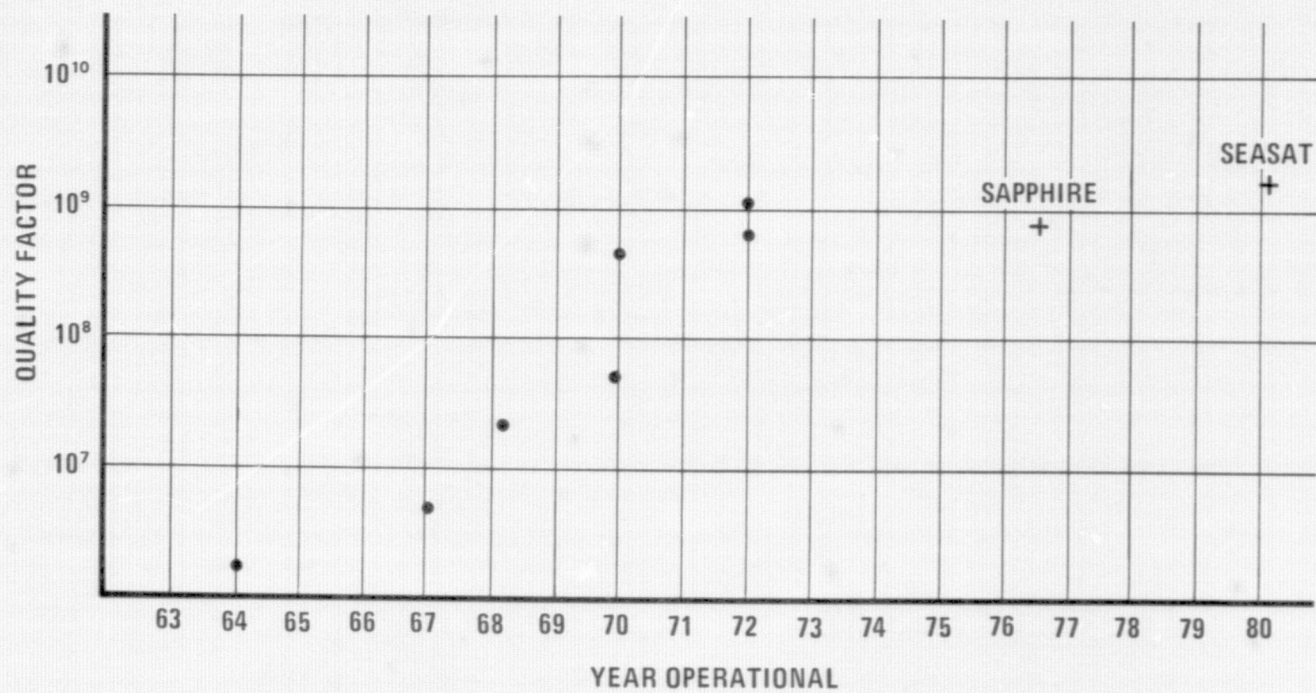


FIGURE 19. SAPPHIRE DIGITALLY PROCESSED IMAGERY



115 128-448

FIGURE 20. SAPPHIRE SYSTEM CONCEPT



1269-2

GOODYEAR AEROSPACE

FIGURE 21. SAR OPTICAL PROCESSOR QUALITY FACTOR HISTORY

N78-14473

A PERSPECTIVE ON THE STATE OF THE ART OF
PHOTOGRAPHIC INTERPRETATION

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ABSTRACT

Aerial photography is the oldest form of what has come to be referred to as remotely sensed data. Aerial photography has the widest operational application, and the most diverse array of techniques and methodologies associated with its interpretation. The aerial camera is the most widely used sensor system today and is typically included with more "unconventional" systems in sensor packages to provide "reliable" documentation of environmental conditions. In a very real sense, aerial photography and photographic interpretation are the cornerstone of remote sensing. This is true even though tremendous advances have been made in the technology of generating images by other than photographic means. Many interpretative techniques used on data from these "more advanced" or "unconventional" imaging systems are essentially extensions of techniques originally developed for the analysis of aerial photographic data. Indeed, as research on the analysis and application of data from other than photographic imaging systems progresses, the role of the interpretation of aerial photography becomes more important. It is these photo interpretation techniques which are called upon to provide the "truth" or verification to substantiate the reliability of the interpretation of the data generated by the new system.

It is essential then, that any individual who wishes to practice the art of remote sensing data analysis gain a thorough knowledge of the activities, elements and techniques of photographic/image interpretation. While the activities and elements of photo interpretation have remained essentially the same, technique development has continued to progress. In addition to a thorough review of these technique advances, I suggest that a more critical appraisal of the "why" and "how" be continued in photo interpretation research. In particular, additional studies are proposed dealing with the basics of interactive process. Finally, a strong plea is made for the new generation of remote sensors to acquire a good background in manual techniques lest he become graphically illiterate, relying too heavily on computer capability or on just photo or image reading rather than photo/image interpretation.

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INTRODUCTION

This paper will deal with the current state of the art of aerial photographic interpretation. Manual photo interpretation techniques will be emphasized as they are the most widely employed types of analysis in use today.

This paper begins with a brief synopsis of the development of photographic image interpretation. This is followed with an extended discussion of the basic tasks of the photo interpreter, the elements of photographic interpretation and the techniques of interpretation. Some readers may feel that so much emphasis on technique is inappropriate for a perspective on the state of the art such as this. Obviously, I disagree! Today, in my opinion, I see too many "remote sensors" who have little background or practical experience in actual nuts and bolts photo interpretation. Here I believe the old saying "you need to know how to walk before you can run" applies. I feel that many individuals who come into the field today get swept up in the automated "let the machine do it all" mystic. This is not to say that automated techniques do not have their place. They do, and will be briefly discussed later. But I believe that a thorough grounding in the activities, elements and techniques of photo interpretation is essential for any and all who would practice the art of remote sensing. Lastly, the paper concludes with a brief analysis of the state of the art of photo interpretation and a discussion of possible future research directions.

Image interpretation, which to me includes the analysis of photographic data, can be defined as the act of examining images for the purpose of identifying objects and judging their significance. It is interesting to note that in the glossary of the Manual of Remote Sensing, Reeves (1975) defines photo interpretation such that image interpretation is one widely used form under it. The Manual gives no specific definition of image interpretation in and of itself. Aerial photographic interpretation differs from direct observation in areal scope, perspective and temporal relationships. It is similar, however, to direct observation in one critical respect; the amount and reliability of the information obtained depends upon the training and aptitude of the observer and on the nature and complexity of the scene observed. It is axiomatic that the more knowledge the photo interpreter has concerning:

- ° the systems and interactions which combine to produce the photo he is analyzing;
- ° the elements and techniques of photo interpretation; and,
- ° the overall goals of his interpretation

the higher the probability that his interpretations will be correct. Photo interpretation, like statistics, is basically a technique by which probabilistic statements can be made about objects, phenomena and relationships which may exist in our environment.

Aerial photography is the oldest form of what has come to be referred to as remotely sensed data. As such it has the widest operational application and the most diverse array of techniques and methodologies associated with its interpretation. In a very real sense the interpretation of aerial photography remains the cornerstone of remote sensing. This is true even though tremendous advances have been made in the technology of generating images by other than photographic means. In addition, many interpretation techniques used on data from these "more advanced" or "unconventional" imaging systems are essentially extensions of techniques originally developed for the analysis of aerial photographic data. Indeed, as research on other than photographic imaging systems progresses, the role of interpretation of aerial photography becomes more critical. These are the techniques which are often called upon to provide the "truth" or verification to substantiate the findings of the interpretation of the data generated by the new system. Thus, the aerial camera is the most widely used sensor system and is typically included with more "unconventional" systems in sensor packages to provide "reliable" documentation of environmental conditions.

The Manual of Remote Sensing defines a photograph as: "A picture formed by the action of light on a base material coated with a sensitized solution which is chemically treated to fix the image points at the desired density. Usually taken to mean the direct action of electromagnetic radiation on the sensitized material." On the other hand, the Manual defines an image in two ways: "(1) the counterpart of an object produced by the reflection or refraction of light when focused by a lens or mirror; (2) the recorded representation of an object produced by optical, electro optical, optical mechanical or electronic means." The term image then, is generally used when electromagnetic radiation emitted or reflected from a scene is not directly recorded on film. Thus, the Manual draws a distinction between a photograph and an image; however, in common usage the somewhat broader term, imagery, is often seen as it will be here, to include "photography." Although most of the techniques of photo interpretation discussed in this paper relate to the interpretation of any graphic presentation, the author will attempt to confine his remarks specifically to the interpretation of aerial photography. In some cases, however, such as the discussion of the multiconcept, material on the comparative analysis of images from other sensor systems will be included. In addition, this paper presupposes that the photography supplied to the interpreter is sharp and otherwise of good quality. There are numerous commercial firms in the United States and the world capable of consistently producing high quality aerial photography. Indeed, of the operational remote sensing programs carried out in this country today, more than 90 percent are being carried out utilizing photographic data either primarily or exclusive of other types of imagery. It is the analysis, annotation and application of these data using principally manual photo interpretation techniques which have helped spur the development of the more advanced imaging systems and the interactive automated analysis techniques which are coming more and more into use today. Automated image analysis techniques can also be employed in the analysis of aerial photographic data if the photography is digitized. Such digitized data can then be processed automatically. The process of digitization, however, typically lowers both the spatial and spectral resolution of the photographic data; and because systems are available to provide digitally recorded spectral information for the photographic portion of the electromagnetic spectrum, the author sees little value in discussing the digitization process in the present paper.

DEVELOPMENT OF PHOTOGRAPHIC INTERPRETATION

The first aerial photograph was taken from a captive balloon by Gaspar Felix Tournachon in 1858. It is said that he was planning to produce a topographic map from his photos. He succeeded in photographing the village of Petit Bicetre, France. The first aerial photo taken in the United States was taken by James Wallace Black and Samuel King over Boston in October of 1860. In both of these photos considerable detail is available to the viewer. Oliver Wendell Holmes immortalized the Black photo by describing it as "Boston...as seen by the eagle and wild goose." It is interesting to note that aerial photography was acquired from a rocket before photos were taken from aircraft. In 1906, Albert Maul took the first photos from a rocket propelled by compressed air. It was not until 1909 that Wilbur Wright took the first aerial photography from an aircraft. Wright took the pictures with a motion picture camera.

Colwell, in the Manual of Remote Sensing states that as of 1950 remote sensing techniques were essentially the same as they were for the entire century subsequent to the acquisition of these first aerial photographs (Colwell, 1975). Either a single or multiple photo (for stereoscopic viewing) were employed to study the area of interest. The photographic scale was usually 1:20,000 and the actual ground resolved distance on the order of 1 to 2 meters. The entire system used by the interpreter, for information extraction was somewhat of a compromise between what he wanted to report and what he was able to report with acceptably high accuracy in view of the limitations imposed upon him by the resolution and contrast characteristics of the photography (Colwell, 1975).

During this period, between 1858 and 1950, applications of aerial photo interpretation grew and diversified spurred on mainly by applications to mili-

tary information requirements. However, for the non-military community, the most important feature of this situation was the training of thousands of geographers, geologists, foresters, engineers and others in World Wars I and II. It is these individuals who either during or following their military careers began to truly expand the applications of aerial photographic interpretation.

There are far too many examples of the applications of the product of photo interpretation to detail here so I will only briefly summarize some early uses. As early as 1922, Lee (1922) pointed out some of the potentials of aerial photography for analyzing physical and cultural features. Joerg (1923) pointed out their utility in urban research while Johnson and Platt (1930) drew attention to the use of air photos in archaeological research. During the 20's air photos were also used by petroleum geologists and the applications grew rapidly (Miser, 1940). By the 1930's air photos were being used by most branches of the earth and agricultural sciences. Government agencies began to use aerial photography to map the country and provide payment for farmers participating in crop payment programs. In these years and those immediately following, heavy emphasis began to be placed on the development of photo interpretation techniques and this has continued up to the present. As previously stated, World War II provided considerable impetus to photographic interpretation and initiated the era of image analysis as other than photographic imaging systems began to come into use.

Thus, we come to the period that ranges from the 1960's to the present. During this time we have seen a tremendous expansion in the diversity of images and in the analysis technique options available to the analyst. During this period, as stated previously, the importance of the interpretation of aerial photography has continued to increase. The enunciation of the multiconcept by Colwell (1975) in the Manual of Remote Sensing is a good example of the type of advanced interpretation techniques/methodologies being developed to take advantage of the range of platforms, systems, and format options open to remote sensing scientists today.

ACTIVITIES OF PHOTO INTERPRETATION

If we were to analyze the interpretation process as though it occurred in a time sequence, the analysis typically begins with the detection and identification of important objects. The objects may then be measured manually or with the aid of appropriate instruments. Measurement could then be followed by a consideration of the objects in terms of information from the interpreter's special field of knowledge. The interpreter must then be able to communicate both his perception of objects and the significance of the objects.

Identification

There is a general rule of thumb in image analysis which goes as follows: it takes 3 resolution cells along the side of an object to detect it. It takes 5 resolution cells along a side to identify it. The process of detection and identification are very difficult to describe. Each individual may go about the psycho/physiological process of identification in a different way. Clues such as size, shape, tone and texture while important to one individual, may be meaningless to another. The interpreter communicates his response to a stimulus by mentally labeling the identified object. His ability to identify objects cannot be measured in the absence of labeling, although it is possible to learn whether his response repertoire includes the appropriate label for a given object. In order to communicate adequately his interpretations, the image analyst must be well versed in the terminology of his own and related fields of knowledge.

Measurement

Image interpreters, at times, measure the exact spatial and spectral dimensions of objects by means of scales and other instruments. Generally, measurement in manual photo interpretation consists of either a visual estimate of the size and shape of an object or a detailed metric calculation of shape or density.

Reasonably correct estimation of dimensions are essential to correct identification.

Problem Solving

The photo interpreter is often required to identify objects by the study of associated objects, or to identify object complexes from their component objects. This activity is one form of problem solving. Most problems in photo interpretation require the interpreter to have at his command knowledge derived not only from the photos themselves but from the relevant field or fields of study or to be working closely with individuals with such in-depth knowledge. The systematic arrangement of particular objects and phenomena recorded on aerial photography facilitate interpretation because of the orderly way in which the objects have come into existence on the Earth's surface. A geologic process, for example, gives rise to related features which possess the orderliness of common origin. Plant associations display the orderliness of common environment. Cultural features, associated by their common function, form industrial complexes. Appreciation of the role of orderly associations in the interpretation process proceeds most effectively from a combined mastery of both the interpretation process and background training in physical, biological, or environmental sciences.

ELEMENTS OF PHOTO INTERPRETATION

Aerial photography represents energy reflected in the visible and near visible portions of the electromagnetic spectrum. It is recorded in many shapes, sizes and scales. An understanding of the basic elements of image interpretation is essential to the efficient and effective use of these data.

Tone or Color

Tone, whether shades of gray in a black and white photograph or color as hue, value and chroma in a color photograph, conveys more information to a knowledgeable interpreter than any other single element of interpretation. In almost all cases, it is the difference in tone or color between objects or between an object and its background which is important. Without such a difference in tone or color between the background and the edge of an object, there can be no detectable image. In aerial photographic interpretation we deal with tone as representative of reflected energy. It should be remembered, however, that with the range of sensor systems available today, tone on an image can be the product not only of reflected energy but emitted and transmitted energy as well, depending on the sensor system acquiring the imagery.

Size

Size is an extremely important element. By measuring the size of an unknown object on an image an interpreter can eliminate from consideration whole groups of possible identifications.

Shape

The shape or form of some objects is so distinctive that they may be identified solely from this criterion. The Pentagon Building near Washington D.C. is a classic example. However, the shapes of objects seen in vertical view are sometimes surprisingly difficult to interpret. The plan or top view of an object is so different from the familiar profile or oblique view that novice interpreters have been known to fail to recognize the image of the building in which they were working (Estes and Simonett, 1975).

Shadow

Shadows can either help or hinder the interpreter for they reveal silhouettes but may hide detail. Shadows are familiar phenomena and in ordinary life we often judge the size and shape of objects or persons by observing the sha-

dows they cast. Commonly, aerial photographs are taken within two hours of noon (local sun time) to avoid excessive shadows and reveal maximum ground conditions. On the other hand, the presence of shadows normally enhances the photo interpreter's perception of shape and therefore aids in object identification. In some geologic projects, for example, photography has been flown at very low sun angles in order to accentuate minute surface irregularities. This is one reason why side-looking airborne radar imagery which approximates low sun angle photography is important in geologic investigations. Low sun angle terrain accentuation was also a factor in determining the time of day at which Landsat's orbit would be made sun synchronous.

Texture

Texture is created by tonal repetitions in groups of objects which are too small to be discerned as individual objects. Texture, the visual impression of roughness or smoothness created by some objects, is a valuable clue in interpretation. This is especially true on imagery obtained with side-looking airborne radar and imaging passive microwave radiometers where texture can play an important role in differentiating various classes of environmental phenomena.

Pattern

Pattern or repetition is a characteristic of many man-made and some natural features. Pattern is a very scale dependent phenomenon. An orchard which may exhibit a pattern on a low altitude photo may appear as rough textured on a high altitude photo and smooth textured on a satellite image depending on the focal lengths and associated resolution capabilities of the sensor systems employed. A regional tectonic pattern such as that formed by the meeting of the San Andreas and Garlock faults in California may not assume the significance on a low altitude photo that it does on a high altitude photo or Landsat image.

Site

The location of objects with respect to one another or to terrain features is often helpful in narrowing probabilities in image interpretation. For example, swamps typically contain specific vegetation assemblages; distinctive agriculture practices are used when farming hillslopes (e.g. dry farming with countour plowing); thermal power plants are located near a water body. Site is very close to association as an element in image interpretation.

Association

Association is one of the most helpful clues to the identity of man-made features. The manufacture of aluminum requires large quantities of electrical power. Absence of a power supply rules out this industry. Schools usually have associated playgrounds and athletic fields while churches do not. Even the type of school (elementary, secondary, junior high, or high school) can be inferred from the size and type of playing fields, buildings, and parking facilities. Large farm silos are an indication that livestock are (or were) present. Unexpectedly large culverts or bridge spans across small streams indicate that heavy runoff occurs frequently enough to require substantial engineering works.

Height

Most interpreters believe, except for tone, that the third dimension is the most important element in photographic interpretation. The relative heights and 3-D geometric shapes of objects often provide revealing clues as to their identity. We can achieve stereo with cameras and line scanners in the visible and radar regions of the electromagnetic spectrum.

Resolution

Interpreters should treat resolution with extreme care. It is a valid measure of image quality but may not always give an interpreter a true indication of the information content of a given image. Resolution depends on many parameters but it always places a practical limit on interpretation. Some

objects are too small to be resolved, or even if large, may otherwise lack sufficient contrast with their background to be recognizable on an image.

Resolving power depends on many factors. The first and often the most overlooked requirement is that a difference must exist between the energy reaching the focal plane from an object and its background. If there is no difference then nothing that the recording system can do will create a discernible image. In photographic systems, resolving power is also related to the quality of the lens and the spectral sensitivity of the film emulsion, whereas with scanning systems the limitations of resolving power of the imaging tube along with those limitations imposed by the system's electronics and the geometry of the scanning process must be taken into account. Just as the finite size of silver halide grains in a photographic emulsion may be one limiting factor in determining ultimate resolution of film in a camera, so the finite size of a scanning electric beam and the rise time of the electronic amplifiers (the time it takes to switch from viewing an extremely light object to a very dark object) are also resolution limiting.

Resolution can be talked about from many view points. Without going into great detail they are:

- ° GRD - Ground Resolved Distance. Pertains to the length or size of the smallest object which can be seen on a given image.
- ° LPM - Line Pairs Per Millimeter. Pertains to the number of line pairs of progressively narrower widths at a specified contrast ratio which can be resolved by an imaging system.
- ° Acutance - a measure of the sharpness of an image. The human eye likes sharp edges. This technique uses microdensitometry to develop edge gradients for objects in a scene. The more steep the tonal gradient between objects, the easier they should be to differentiate.
- ° Modulation Transfer Function - the point spread function of an image.
- ° Spectral Resolution - pertains to how finely we can discriminate spectral bands within a given region through filtration or other techniques.
- ° Radiometric Resolution - pertains to how finely we can subdivide the levels of energy (often spoken of in terms of temperatures) emitted from objects.

In general, the spatial resolution of aerial photography is directly proportional to: (1) the brightness of the object to be resolved in contrast with the background against which it is imaged; (2) the aspect ratio (ratio of object length to object width); (3) the regularity of object shape; (4) the number of objects comprising the pattern to be resolved; (5) the uniformity of the background against which the objects are imaged; and (6) the extent of the background against which the objects are imaged.

On the other hand, the spatial resolution of aerial photography is inversely proportional to: (1) the graininess of the film; (2) the amount of image motion relative to the film during the instant of exposure; and (3) the amount of atmospheric haze disturbance between the camera lens.

TECHNIQUES OF PHOTO INTERPRETATION

Photographic interpretation has been defined as the act of examining photographs and/or images for the purpose of identifying objects and phenomena and judging their significance. The better the interpreter understands the purpose of his analysis (that is, the specific use to which his analysis will be put), the better job he can do. Therefore, it is important that the interpreter understand the overall task of which his analysis is part. With this knowledge

he may better judge the significance of the objects and phenomena he perceives on the photos he is analyzing. In carrying out his task, an interpreter may use many more types of data or information than those recorded on the photos/images he is to interpret. These data are often grouped under headings such as collateral material, ancillary data, onsite verification or just plain field work.

Collateral Material

There are many sources of collateral material and the interpreter should take advantage of all of these:

- ° material from the open literature (books, articles, reports, maps, census data, etc.)
- ° laboratory measurements
- ° photo interpretation keys (e.g. elimination, selective and descriptive)
- ° field work
- ° other image sources - ground, aerial, space

The interpreter should be careful in the use of collateral material. He must always remember that these data have a variance of their own; and that although collateral material is often used as the "truth" against which remotely sensed data are judged, there are cases where the truth may not be absolute. There may be times when the interpreted image may provide a more accurate record than the collateral.

Stereoscopic Viewing

One of the most used photographic interpretation techniques is stereoscopic analysis. The principle of stereoscopy (depth perception) should be understood by every image interpreter. With binocular vision, when the eyes are focused on a given point, the optical axes of the two eyes converge on that point intersecting at an angle called the parallax angle. The nearer the object, the greater the parallax angle. The shortest distance of clear stereoscopic depth perception for the average adult is about 25 cm. Objects can be focused at distances as short as 15 cm, but such close viewing causes excessive eye-strain. The maximum parallax angle formed by the eyes is approximately 15°. The maximum distance at which distinct stereoscopic depth perception is possible is approximately 500 m for the average adult. Beyond that distance, parallax angles are extremely small and changes in parallax angles necessary for depth perception cannot be discerned.

An image interpreter can create a three-dimensional or stereoscopic model of terrain by viewing overlapping imagery. The photographic basis for stereoscopy are the principles of image displacement and stereoscopic parallax. These topics are beyond the scope of this brief discussion. It is important, however, to restate that many interpreters consider height or the ability to achieve stereoscopic analysis, as one of the most important aspects of photographic interpretation.

Methods of Search

There are two basic general methods which may be used to study aerial imagery: the "fishing expedition" and the logical search.

Image interpreters have learned that aerial photography and remote sensing imagery is full of surprises. They are often tempted to examine every object in every photograph so as not to miss anything. This is the fishing expedition; a method of search that is not frequently used. Fishing yields large amounts of information, including much that is not pertinent to the subject at hand. It requires a more leisurely effort than the interpreter can often afford.

By resorting to probabilities, the interpreter can work more efficiently in the time available. He searches only those areas in which the objects of interest are likely to be found, and disregards large regions or entire images which are not likely to contain desired information. This selective method is logical search, a combination of quick scanning and intensive study. It demands more experience than the fishing expedition since the interpreter has to decide where intensive study will yield the best results. In general, however, it is much more productive in relation to the time and effort expended.

A knowledgeable interpreter typically begins his task by a close examination of all details thought to be relevant. Most experienced interpreters prefer to begin by scanning the area as a whole. They are then prepared for intelligent selection and the study of detail. In most instances the interpreter will then follow the following guidelines:

1. Proceed from general considerations to specific detail.
2. Proceed from known to the unknown.
3. Work methodically.

Again, however, care should be taken in proceeding from general to specific considerations. This is desirable as long as the considerations of general (sometimes called regional) features do not bias the interpretation of the specifics. Specific, local considerations often provide evidence needed to complete or confirm the broader regional pattern. In most cases, general and specific features must be considered together. To say that one must come before the other can be misleading. To go further than this and propose that interpretation should proceed from one specific group of features to another is an unwarranted channeling of the infinite variation that the interpreter encounters (Olsen, 1973). Working from the known to the unknown is basic in all science. Often known objects or phenomena provide important clues to the identity and significance of unknown objects and/or phenomena. Finally, by proceeding methodically there is less chance that the interpreter will fail to detect details significant to his task. By proceeding in a logical, methodical manner always bearing in mind the final goal of task, the interpreter is far more likely to achieve significant results than if a nonstructured analysis was conducted.

The Use of Multiple Images

Advances in sensor and platform technology have increased the amount and types of information available to the image interpreter. Sensor systems currently being used are capable of presenting the interpreter with a visual representation of energy emitted, reflected and transmitted at wavelengths outside the visible portion of the electromagnetic spectrum and therefore beyond direct visual experience. Available sensor platforms can acquire image products at a variety of scales. The impact of these technological advances has been to confront the interpreter with a multiplicity of data for interpretation.

Colwell in Chapter 1 of the Manual of Remote Sensing (1975) discusses the broad outline of what he calls the multiconcept as applied to the acquisition and analysis of any or all types of remotely sensed data. Components of the multiconcept include imagery acquired from, analyzed by, or employed for:

- | | |
|--------------------------------|---------------------|
| * multistation (multiplatform) | * multidirection |
| * multiband (multispectral) | * multienhancement |
| * multirate | * multidisciplinary |
| * multistage | * multithematic |
| * multipolarization | * multiuse |

While these concepts are germane to photo interpretation, they apply equally well if not better to image analysis and will be discussed in some detail here.

Multistation (multiplatform) - is the act of obtaining imagery of a given area from more than one perspective. This produces the parallax important for stereoscopic viewing. Multistation can also be used to connote the acquisition of imagery from multiple platforms. Today we have the capability to acquire images from a variety of platforms (towers to helicopters to aircraft to satellites) at all altitudes (from low to satellite).

Multiband (multispectral) - this concept is basic to the interpretation of multiple images. It originally formed the basis for the multiconcept. Stated simply, the multiband concept suggests that the level of energy reflected, emitted and transmitted by objects normally varies with wavelength throughout the electromagnetic (EM) spectrum. The signature of an object on an image is governed by the amount of energy received by the sensor within the wavelength range in which that sensor produces images. Therefore, a unique tonal signature for a particular object may be identified if the energy that is being emitted, reflected, and/or transmitted from it is broken down into carefully selected wavelength bands.

The multiband concept as a term, is often applied to the analysis and/or acquisition of imagery from within a particular wavelength region of the EM spectrum, e.g. visible, ultraviolet, or thermal infrared. Another term which is quite similar and often applied to the acquisition and analysis of images from more than one wavelength region of the EM spectrum is multispectral remote sensing. The term multispectral image analysis is commonly used to denote the analysis of imagery created by energy from one or more bands, from more than one spectral region (e.g. using color aerial photography in conjunction with thermal infrared imagery to analyze the thermal and suspended sediment patterns in a water body). Just as two or more bands of imagery acquired within the visible and near-visible portion of the electromagnetic spectrum may provide the image analyst with more information than a single broad-band visible photograph, so it follows that the combined analyses of images acquired in the ultraviolet, and/or thermal infrared, and/or microwave bands could also increase the amount of information extracted by the interpreter. It is important, then, for the image interpreter to become aware of the important imaging characteristics of not only photographic systems but a variety of other sensor systems as well. This potential for the derivation of unique tonal signatures through the use of sensor systems with sensitivities in a variety of spectral regions can enhance significantly the probability of making correct interpretations. However, care must be taken not to drown the analysts or interpretation system in a morass of data.

Multidate - Just as the recording of data in various bands of the spectrum can provide valuable information to the image interpreter, so too can the recording of energy from the same area through time. Photo interpreters/image analysts are coming to the realization that time is one of the most important discriminates leading to the identification of environmental phenomena. Simonett and Evertt (Lintz, Jr. and Simonett, 1976) discuss what they term the environmental modulation transfer function concept. Simply stated, this concept proposes that there is a wide range of temporal environmental variability which makes it difficult to achieve a uniform class of information extraction when a single spatial, spectral, or temporal (using both reflected, emitted, or transmitted energy) resolution is fitted to a functional categorization of a specific environment. Many features exhibit unique changes with the passage of time. For example, it may be difficult even with the use of multiband, multispectral imagery acquired on a single data to discriminate and identify the mix of agricultural crops growing in a particular area. If multiple image acquisition missions are coupled with a knowledge of the crop phenological cycles (crop calendar) of the area under investigation, identification is improved. This is true because crops grown in an area generally exhibit unique temporal growth characteristics which, if known can aid in identification. Changes in urban areas, flood or disaster evaluation and monitoring changes in coastal morphology are examples of studies in which the interpretation of multidate imagery can add significant information.

Multistage - This pertains to the acquisition of photography at different scales. This photography may then form the basis of multistage sampling which is an effective tool used in large area surveys. Today, remote sensing can provide the means to obtain reliable estimates of large areas from relatively small samples. In forest and agricultural surveys, aerial photography has long been used to improve sampling efficiency. Among the techniques employed are:

- * Stratified sampling (where strata are defined on the photos by delineating relatively homogeneous areas);
- * Double sampling with stratified sampling at the first phase; and
- * Double sampling with regression.

As previously stated, image interpretation is basically an attempt to make probabilistic statements about our environment. It is becoming increasingly necessary that the interpreter become aware of statistical sampling procedures such as those listed above and the use of statistics in general.

Basically, in a multistage sampling scheme, progressively more detailed information is obtained for progressively smaller subsamples of the area under investigation. The method takes advantage of the increasingly finer resolution, which can be provided by the use of either multiple sensor platforms (such as low and high altitude aircraft and spacecraft) or by utilizing a variety of focal lengths from a single sensor platform. Most operational multistage sampling techniques being used today are geared toward the use of medium scale resource photography such as that available from U.S. government agencies. Some, however, are beginning to combine these photographs from traditional sources with Landsat type data. In multistage sampling then, low, intermediate and high altitude images as well as satellite data act as subsamples which can be used to increase the efficiency of the sample selection in each subsequent stage. The precision and accuracy of the estimated information depends solely on the relationships between predictions made by image interpretation and the value of measured characteristics of the sample units used to estimate population parameters (Langely, 1968). It is important to note then that the aerial photographs and thus photo interpretation are typically found at the most detailed or lowest level of the multistage samples forming the basis for higher order statistical evaluations. The methodology is easy to employ. Operationally, the technique is efficient and provides for a greater portion of the work to be concentrated in areas of high value.

Multiple Polarization - Objects exhibit differing characteristics with respect to their ability to change the energy from the sun, which can be considered as vibrating in all planes and filter it so that vibration is strongest in a single plane. This is equally true for both active and passive sensor systems. Water exerts a strong polarizing influence on solar energy and if a spinning polarizing filter is placed in front of a movie camera and imagery is acquired at the proper sun angle all water in a given scene will appear to alternately flash and grow dim making for easy identification.

Multidirectional - Although most modern aerial imagery is acquired from the vertical perspective, there are instances where more information may be obtained if images of the same area are acquired from one or more oblique orientations. This may especially be true when attempting to "see" below the edges of a vegetation canopy; however, it is more specifically true if we are examining side-looking airborne radar data which because of its method of acquisition has shadowing problems. If detailed knowledge of a complete area of moderate to steep relief is to be acquired it may be necessary to fly imagery from as many as four separate look directions.

Multienhancement - It is beyond the scope of this discussion to go into the variety of optical and electronic image enhancement devices, techniques, and methodologies capable of aiding today's image analyst. The reader wishing

more information in this area should consult Chapter 12 in Volume I of the Manual of Remote Sensing (Steiner and Salerno, 1975). Basically, both types of systems take their basic cueing from image tone (with electronic devices, texture discrimination has also been added). The purpose of these devices is to produce a unique tone signature for the object or phenomenon of interest against its background of all other imaged objects or phenomena. These types of devices can be used with either photographic or scanner data which has been recorded in either a digital or analog form. Such techniques when employed in an interactive mode, taking advantage of both man's and machine's capabilities and combining them with image processing and pattern recognition produce a powerful tool for the interpreter.

Multidisciplinary Analysis - It has been stated that remote-sensor data are "one time write-many times read." Basically, this means that one image can be looked at by a number of specialists and each may gain information of value to his particular discipline area. In order to ascertain the agricultural potential of a given area, a team of geologists, hydrologists, pedologists, agronomists, meteorologists, geographers, foresters, and economists, among others, might examine imagery of a given area. By having interpreters representing various discipline specialties interpret imagery in concert, a synergistic effect can be created. For many types of earth-resources analysis the use of the conference system by image interpreters of varying background is likely to produce a more accurate and thorough analysis than could be achieved by a single image interpreter working alone.

Multithematic Presentation - Just as there is a value to the technique of multidisciplinary analysis, the multithematic presentation of data can also be of considerable value to the photo/image interpreter. When we remember that the basic method of communicating interpretations is labeling in either cartographic or tabular form, we can begin to appreciate the significance of this technique. Thus, it may be common in the compilation of a complete analysis of a geographic area to prepare as a separate map sheet, with attached appropriate tabular measurements or statistical data on the following themes: vegetation, geology, hydrology, soils, and land use. In this realm it is also becoming more and more common to see information depicted on a photomap or orthophoto map base. In the years to come we will be seeing more and more of this type of presentation as well as the use of images from other than photographic systems used as a base, as was the case of radar being used as the base for mapping and cartographic presentation in project RADAM.

Multiuse - Finally, as an outgrowth of all of the above concepts, the interpreter should be aware of the range of potential applications to which his analysis may be put. Data from a multithematic presentation such as that discussed above could be used to varying degrees by any number of researchers or decision makers at many levels including planners, agronomists, range managers, hydrologic engineers, and so on.

Use of the multiconcept can place a considerable burden on image analysts unless extreme care is taken to design the most efficient package of sensor platforms and dates of image acquisition for a given task. It may be good to get all types of images from all altitudes on every date if possible but the potential for miring the interpreter in a morass of irrelevant data is great. The emergence of the multiconcept, indeed the emergence of the range of potential images which can be placed before the analyst, demands that the level of environmental and systems sophistication of the interpreter be dramatically increased. This is why in many colleges and universities, airphoto interpretation and remote sensing curricula are being expanded to more than the traditional photo interpretation or remote sensing courses.

Convergence of Evidence

Photo interpretation is basically a deductive process; features that can be recognized and identified directly lead the image interpreter to the identification and location of other features. Even though all aspects of an area are irreversibly intertwined, the photo interpreter or image analyst must begin

someplace; he may begin with a consideration of drainage, landforms, vegetation, and man-made features, then go on to other topics of interest integrating each of the facets of the terrain as he goes. For each terrain, the interpreter must find his own point of beginning and then consider each of the various aspects of the terrain in logical fashion.

Deductive image interpretation should entail a thorough understanding of all of the activities and techniques of image analysis as well as the conscious or unconscious consideration of the elements of image interpretation listed earlier. The completeness and accuracy of image interpretation are a function of the interpreter's understanding of what techniques were used to acquire the imagery, what collateral material is appropriate, and how and why images exhibit shape, size, tone, shadow, pattern, and texture characteristics. In addition, an understanding of site, association, and resolution strengthens the interpreter's ability to integrate the different features making up the terrain. For the beginning interpreter, knowing all of the techniques of image analysis may be a formidable requirement. Hence he should systematically review the elements of image interpretation to proceed with an integrated terrain interpretation in an optimal fashion.

The principle of convergence of evidence requires that the interpreter first recognize basic features or types of features and then consider their arrangement (pattern) in an areal context. Several interpretations may suggest themselves. Critical examination of the evidence usually shows that all interpretations but one are unlikely or impossible. The greatest difficulty in interpreting images involves judging degrees of probability. As previously stated, the more the interpreter understands the techniques and elements of image analysis, as well as where his task fits into the overall goal for which he is interpreting the image, the higher his probability of correct analysis becomes.

SUMMARY AND PERSPECTIVE

Simply because basic aerial photographic interpretation has changed little over the past 100 years does not mean that we have achieved perfection, answered all the questions, or indeed even know what some of the questions are yet. It is true that tasks remain the same, detection of an object or the occurrence of a phenomenon, identify it, possibly measure it, and judge its significance. The elements of tone, texture, pattern, etc. also remain the same. What has changed however, are the techniques of photo interpretation and the emphasis placed upon specific techniques. Although today we still see aerial photography as the remote sensor system employed in the large majority of operational applications, we also see aerial photography being used as the "truth" or standard against which imagery from less conventional systems are compared.

I therefore make a strong plea for more emphasis on the teaching of the basics of photo interpretation. Too many courses, texts, and individuals in the field of remote sensing tend to gloss over the basics as being too mundane or "easy to pick up." I contend that a thorough knowledge of the basic philosophy which is an integrated part of activities, elements, and techniques of photo interpretation, is essential if we are to truly advance the state of the art of photo interpretation. Too many of us think manual interpretation is easy or straight forward. It is not! Many times it is tedious, often exciting, but for the really significant problems it requires intelligence, ingenuity, and knowledge of elements and techniques presented herein to achieve the desired information for the user. We should remember also that most, if not all of the operational applications of aerial photographic interpretation are performed using basically manual rather than automated image analysis techniques. I see this situation continuing into the foreseeable future.

There is a real need, however, to go into considerably more depth than we have in the area of man/machine interactive processing of images in digital and analog formats. The human mind is an excellent interpretation system and its capabilities properly employed can go far in helping to upgrade the accur-

acies of many image processing algorithms. Although many individuals pay lip service to the idea of interactive processing, I believe few truly understand the significance and potential of the concept; while many still rely on interpretation as being either manual or automated. A great deal of research is still required in this area if we are to progress. Research on topics such as: what are the optimum formats for data presentation to the interpreter; what type and depth of training must the interpreter have to effectively accomplish interaction; are there psycho/physiological barriers to effective interactive processing; should be accomplished. In addition, if only this much is done, both the interpreter and the systems analyst acquire a basic, thorough understanding of each others techniques, methodologies and goals, we will have already taken a large step forward.

I also see a greater and more significant merging in the photographic and cartographic areas. The use of orthophotography for interpretation purposes, provides a significant merging of interpretation and photogrammetry. Recent studies such as those by Thrower and Jensen (1976) describe the potential of orthophotos while Jensen (1976) more specifically documents the relative ease of interpreting objects and areas on aerial orthophotography. Jensen's conclusions strongly suggest that for the skilled as well as the unskilled interpreter, probabilities of more accurate interpretations are increased for certain tasks when orthophotos are interpreted as opposed to conventional photogrammetric line maps.

To some extent the studies of Jensen (1976) deal with the psychology of picture perception. Researchers attempting to advance the state of the art of photo interpretation must keep abreast of studies in psychology (e.g. Kennedy, 1974; Blaut, et al., 1970) and combine this with a knowledge of studies in physiology (e.g. Morton and Stark, 1971; Michael, 1969) as well. It is a knowledge of these areas which will help us to expand our understanding of the "how" of photo interpretation.

Briefly, continuing along this line, I see a predominance of emphasis today on the "what" of photographic interpretation rather than the "how." We as researchers have spent a great deal of time in recent years on the techniques and applications of photo interpretation but little on such topics as:

- ° How do we determine the credentials of a qualified photo interpreter?
- ° How can we best train a person to interpret a photograph?
- ° How can we find the optimum conditions conducive to the analysis of photographic data?
- ° How should an interpreter conduct visual search?
- ° How do we determine the optimum method for the recording of an interpreters output product (labeling)?
- ° How can we find whether a significant relationship between search time, scales, types of photography and tasks exists?

These are but a few of the many questions which should be answered not just for photos but for the interpretation of all images as well. Many of these questions have been looked at in the past in scattered studies. Yet these are questions which I feel at present remain without satisfactory answers. Each of these questions demand thorough, careful consideration. As a University Professor, I feel that a master thesis or even a doctoral dissertation could be structured around each.

In the Manual of Photographic Interpretation, Lundahl and Monsour discuss their perceptions of the future of photo interpretation as of the late 1950's. Their major conclusions include:

- ° The future of conventional forms of photo interpretation are assured in both the civilian and military areas of endeavor.

- ° The increased use of photo interpretation will be stimulated by the financial savings which the technique offers when compared with conventional ground survey methods.
- ° The continued and expanded use of conventional forms of photo interpretation does not include the entire future of the field. There will be an increasing need for interpretation of data from other than photographic systems.

Their final discussion deals with the importance of photo interpretation in future space travel (at the time the Manual was written, the first crude television pictures were being returned to earth from a satellite). Quakenbush (A. Ed., 1960), Lundahl and Monsour conclude by stating that "It will be a momentous day when the photo interpreter looks at large scale stereoscopic photographs of the other side of the moon; or at the surface of Venus, forever obscured from earth-bound telescopes by its perpetual cloud cover; or the canals of Mars; or the bands of Jupiter; or the rings of Saturn; or perhaps even the forms of life that are evolving on some planet in a distant solar system where the environment is so much like that on Earth that humans could live comfortably." The authors of these prognostications were remarkably astute. Each of their major predictions has to a very real extent come to pass. Only their final prediction remains to be truly fulfilled, although one could argue that it certainly has been fulfilled in spirit.

As I look into the future, these are the things which I see as probable. Some I believe present real potential, others present pitfalls which should be closely watched.

- * Higher resolution space photography and/or imagery from advanced scanners, imaging synthetic aperture radar systems, or cameras utilizing the optical bar principle giving us both high resolution and wide are coverage.
- * The expanded application of information extracted from aerial photographs and other sensor systems in environmental models. Indeed, image data will be increasingly employed to improve the sophistication of our environmental models by distributing model input data more appropriately across space than was possible with point source or lumped parameter models.
- * The continued and expanded use of photo and image interpretation by planners and decision makers at the federal, state and local levels.
- * The establishment of a national and international geobase information system with aerial photography and other remote sensor data forming the primary inputs.
- * The increased use of photos and/or information from unconventional imaging systems by regulatory agencies charged with the protection of our environment.

Aerial photographic interpretation still holds great promises for the ultimate benefit of mankind as we monitor the earth's increasing population and dwindling resource base. It permits the super powers to keep track of each other's strategic potential, hopefully, as Phillip Klass in his book Secret Sentries in Space (1972) contends, decreasing the potential for nuclear holocaust! But as with many beneficial technologies, image interpretation presents a two-edged sword. At what point does the gathering of data on environment resources constitute an invasion of privacy? Can the techniques and methodologies developed through the years for the benefit of mankind be turned against man? Does the future road on which image analysis is taking us lead to the Shangri La of Hilton's Lost Horizons or Orwell's 1984? Although we have come a long way in photo/image analysis, I believe that we have only scratched the surface. There is still a great deal to do.

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GEOLOGIC LINEAMENTS: REMOTELY SENSED

BONANZAS AND EXTRAVAGANZAS

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Lineaments have been discovered or imagined on most new forms of geologic or topographic data bases over the last 1 1/2 centuries. The discoveries reached a high level of sophistication early in this century with W.H. Hobbs, who saw and described on topographic maps essentially the same kinds of lineaments which subsequently have been discovered on air photo mosaics, radar imagery, thermal IR imagery, and on satellite imagery of various types. Skeptics have usually been more numerous than believers of lineaments but the number of believers commonly increases briefly for a time after each new data type becomes available. This has been especially true for the ERTS imagery where only a relatively low level of imagination is required to see linears. Most remote sensors could map dozens of new lineaments on an ERTS frame and become instant true believers. Unfortunately many made the all too common assumption that features with such widespread development must have profound scientific and economic importance, an idea not likely to be discouraged by those trying to justify space expenditures to the nation. A flood of lineament papers poured into the literature, a flood characterized more by the wide extent of its areal coverage than by the intellectual depth of its treatment. The time for some of the flamboyant promises of lineament analysis to be realized is now at hand and many true believers have become devout skeptics. Lineaments are beginning to have a very bad name in remote sensing circles (they have always had a slightly tainted image in geologic circles). Because of the excesses of the last few years we are now in danger of seeing lineament analysis with some of its real but less spectacular values being rejected completely.

Where visible, most of the ERTS type lineaments appear to be quite unspectacular zones of intense jointing or very minor faulting, localizing groundwater movement, deeper weathering, and possibly very minor mineral concentration. A few may be related to true bonanzas: the Albion-Incipient trend of Michigan yields major hydrocarbon production from a fracture related porosity zone; the large new Bluebell oil field of Utah is along a major lineament in the Green River Shale; many major ore bodies are localized along some fracture trend. However, the ERTS type lineaments are far too numerous and our ability to distinguish among them is too limited to use them as simple indicators of bonanzas. Instead we should consider the lineaments as indicators of very small scale fracturing and apply them to problems of comparable scale: localization of bad roof problems in tunnels and mines; water well location; potential extensions of known ore prospects; localized zones of migration in oil and gas fields; zones of more rapid spreading of underground coal fires; locations of potential foundation problems in power plant construction; or zones of potential leakage near dams.

In brief, if we can improve our methods of handling these features and cut down our expectations about them, they may become a reliable work horse of remote sensing. The words of the old economic geologist, Josiah Spur are appropriate, "Geologists are free with extravaganzas, but only God can make bonanzas."

COMPARATIVE PLANETOLOGY -- IDEAS AND METHODOLOGY;
THEIR APPLICATION TO TERRESTRIAL GEOLOGIC PROCESSES

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ABSTRACT

The Moon, Mars and Mercury have been studied intensively during the last decade. Studies of Venus and the satellites of Jupiter and Saturn will be done shortly. In the planetary bodies studied to date, several common features are observed: They are all heavily cratered by impacting debris; the crater flux was very high during the early histories of the planets and then dropped off rapidly; cratering continues to the present. All bodies are highly asymmetric with ancient, heavily-cratered "continental" rocks forming part of the planet and younger, lowland-basalt flows, like the Earth's ocean basin floors, covering the remainder. Study of returned lunar samples, and orbital geochemical and geophysical data has led to the hypothesis of evolution of the terrestrial planets: 1) accumulation followed by continued, less intense impact cratering; 2) differentiation into core, mantle and crust; 3) early mantle convection leading to redistribution of the continental rocks and flooding of the lowlands by basaltic lava flows; 4) continued tectonic and volcanic activity; 5) and on Mars and perhaps Venus, redistribution of weathered and eroded sediments into regional and local eolian blankets. The earliest remote sensing tool used in planetary exploration was imaging data at various scales, that is now correlated and enhanced by computer techniques.

In addition, some 30 lunar data sets derived from remote sensing observations have been reformatted and made computer compatible to permit manipulation. Cross correlation studies and color contour displays have been made for the lunar geochemical and geophysical consortium. These data sets are displayed and enhanced using the same techniques used for computer enhancement of images. This is a very powerful method for manipulating large data arrays in order to bring out similarities and differences. Similar techniques are being applied to Mars and Venus data sets.

The geologic evolutionary processes mentioned are well seen on the Moon, still better developed on Mars, and best developed on Earth. Mercury lies between the evolutionary stages of the Moon and Mars and Venus' position in the evolutionary sequence is still uncertain. The Earth must have passed through similar early evolutionary episodes. A search should be made for remnants of Earth's ancient crust where a record may be retained of the early intense impact history and the first planetwide differentiation. Very large impact craters that record this early history have been found in Canada, the USSR and South Africa. Additional remote sensing and ground studies may augment our understanding of the early history of the Earth.

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INDUSTRIAL USE OF GEOLOGICAL REMOTE SENSING FROM SPACE

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1. INTRODUCTION

When asked to present a paper outlining the industrial use of geological remote sensing from space, I thought I would present a systematic elucidation of what the geological industries are doing with space imagery. Such a discussion would include who is doing what with what type of equipment and what kind of techniques. In fact, The Geosat Committee, which I represent, was formed in August of 1976 to determine what the geological industries need in space imagery in order to relate such needs to NASA. In order to determine what is needed, The Geosat Committee is currently conducting a detailed current and future use poll of its approximate 100 corporate members and this data will be available by June 1977.

But, in preparing the required summary for this paper, which you may have seen, I found that in order to explain the geological industries' use of space remote sensing, I had to first clarify a number of public misunderstandings regarding the geological industries themselves. In fact, in reflecting on what we presently do know about the level of use of space imagery as represented by our 100 member corporations, I perhaps should change the title of this paper to the Industrial Under-Utilization of Geologic Remote Sensing from Space.

I am hopeful that this presentation today will be successful in its attempt to clear up some of these public misconceptions regarding the geological industries. In so doing, I also hope to explain the present level of space imagery use by the geological industries and to predict how this use will change in the near future.

II. GEOLOGIC MAPS

Industrial use of geological remote sensing from space involves all industries who require basic non-renewable resources and support exploration for these resources such as oil, gas, geothermal and minerals. Also included are the mining, petroleum, and civil engineering and environmental industries who are also significant users of geological information. A common theme connecting all of these industries is their indispensable reliance on the availability of sound and accurate geological maps.

Geological maps are used to present a four-dimensional interpretation of the geology of the earth's upper crust as exposed at the essentially two-dimensional earth's surface, which is usually all that can be directly sensed or observed at ground surface or above.

The four dimensions of a geological map include the obvious two dimensions of length and width of a given geological unit, i.e., rock formation, as depicted on a map. The third dimension is that of geologic structures, such as anticlines, synclines, and faults which give the dimension of depth. It is reasonable to state that only those who can think in three dimensions can succeed as geologists. But, implicit in constructing three-dimensional geologic maps is the essential fourth dimension of geologic time. Without an understanding of geologic time, one cannot correctly relate one geologic rock unit to another and then one cannot accurately determine the structural geo-

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logic history of an area. Without such information, an accurate geological map is impossible. Thus, to be a successful geologist and explorationist, one must not only be able to think in three dimensions, but also one must have a firm understanding of geologic time. Obviously, most of us geologists have a very specific perspective of time and mankind.

But, how do such four dimensional geological maps and understanding relate to the problem at hand, that is, the exploration for our declining non-renewable resources and the engineering for such resource development as well as for geological hazards and other environmental concerns? Geologists need such four-dimensional maps because their exploration targets, such as ore deposits and oil fields, occur primarily beneath the earth's surface. That is, their subsurface existence must be interpreted prior to discovery.

In other words; oil, gas, and mineral deposits are discovered in men's minds. With a few exceptions and some cases of pure luck, explorationists discover deposits by taking all possible four-dimensional geological structural and historical data and interpreting where potential exploration targets may exist. Then, after careful analysis, the decision is made where to stick one's professional neck out and probably his job, and recommend the leasing and drilling of a prospect. For the most part, it is only with the drill or similar other physical sample that one learns the truth of his thinking. A discovery or a bust.

An excellent example of the use of such four-dimensional map data and the mental discovery of an ore deposit is the discovery of the Kalamazoo porphyry copper deposit in Arizona by Dr. David Lowell and Quintana Petroleum Co.

The Kalamazoo ore body is the missing, faulted-off portion of the previously-known San Manuel porphyry copper deposit. The fact that the San Manuel deposit was cut off by a fault was well-known, but geologists had long interpreted that the San Manuel fault had moved in such a way as to project the cut off portion of the ore body out into "present space" whereby it was subsequently eroded away. Lowell, however, developed a geologic map and alteration studies of prospects adjacent to the San Manuel deposit and mentally interpreted that, contrary to the accepted opinion, the San Manuel fault had moved in the opposite direction and that the missing piece of the San Manuel ore body should be under the adjacent property. Lowell stuck his neck out, drilled, and was eminently successful by discovering the missing piece which is now known as the Kalamazoo porphyry copper deposit.

The point of this example is that in spite of all the technology that is available, the discovery of this mine was not by direct observation or sensing of the ore body itself. It was found by the genius of a geologist who, having a good four-dimensional geological map and understanding, correctly interpreted the subsurface existence of a deposit.

Many geological engineering and environmental problems such as mine engineering and development, dam site civil engineering and location, nuclear plant site location, waste disposal, seismic studies and strip mining, etc., also require three- or four-dimensional geological understanding of the earth's upper crust and surface.

In developing Landsat and other supplemental geological remote sensing systems from space, it is important to realize that such systems can directly help to produce the required four dimensional geologic maps. However, it must be understood that these systems are only tools to be used as a part of integrated exploration and engineering programs which ultimately lead to discoveries and solutions. Space sensors, for the most part, will not directly find oil, gas, and mineral deposits or solve geological problems. But, the application of properly designed sensors in space can potentially add invaluable data to the geological industries and indirectly assist in the successful exploration for deposits of non-renewable resources and solutions to pressing engineering and environmental geological problems.

III. SPACE TECHNOLOGY AND GEOLOGY

Any tool or technological capability which will assist in making better geological maps more efficiently and more economically, will, in time, be strongly supported and used extensively in conjunction with other tools and techniques by the geological industries. Because geological remote sensing from space is used to make geological maps for exploration interpretation, no direct statement can be made as to how many oil wells or copper deposits will be found by such systems. Although, estimates concerning the dollar value of the improvement in exploration efficiency can be made, no realistic cost/benefit, bottom-line statement can be made as to the true potential benefit in terms of new oil, gas, and mineral studies. However, if only one porphyry copper deposit or one 100 million barrel oil field is found, the cost of these space systems would be more than paid for. And in either case, neither discovery would solve our national energy or mineral crises. It is time to realize that the United States is in a heck of a predicament, resource-wise.

Unfortunately, to compound this situation, our geological industries have been historically slow in picking up new technologies. This is, among other reasons, principally because exploration programs are planned years in advance. There, the sudden advent of a new technology leads to its utilization a few years down the road.

An excellent example of such technological slowness is that of Dr. Arthur Brant, Chairman of the Board, The Geosat Committee, Inc. Among many technological achievements credited to Dr. Brant, is IP, or induced polarization, a principal geophysical tool used around the world today. It took about 20 years for this very important exploration tool to be recognized and generally accepted.

Unfortunately, regarding NASA and space remote sensing, NASA's incredible technologies, such as the Shuttle program, are here and our geological industries are not quite ready for them. NASA's present remote sensing technology as exemplified by ERTS-1 and Landsat 2 have been developed far more rapidly than they could have been reasonably absorbed with proven results by the geological industries. This is because of the aforementioned ingrown infrastructure of exploration and engineering programs and techniques and the inherent indirectness and long-term payout effectiveness of the application of space remote sensing to geological needs.

Within the industries, it is generally recognized that it takes five to ten years from initial exploration to operational development to bring in new mines or oil or gas fields. Given the minimum of three years to develop a new space system, any new sensor needed by the geological industries will potentially create new resource reserve additions eight to thirteen years after acceptance and approval.

The above numbers are critical. It is generally believed within the industries that the United States has remaining (exclusive of imports) approximately a ten to fifteen year reserve of oil and gas, and a fifteen to twenty year reserve of major mineral resources.

IV. THE CHANGING SCENE

The situation regarding the geological industries acceptance and utilization of geological remote sensing from space is rapidly changing. The tremendous potentialities of these technologies are beginning to be recognized. However, a "go it slow" feeling still prevades portions of the geological industry because of the broad geological oversell in the past of the present agriculturally dedicated Landsat systems. There is currently a need to fully test the present and planned Landsat systems, as well as, new proposed sensing capabilities optimized more for geological needs. In general, the geological industries are rapidly applying what is available and learning what can and cannot be done with present systems and what capabilities should be added to the presently planned systems to maximum effectiveness. The Geosat Committee

currently is embarking on a Joint Test Case Study with NASA to further evaluate the geological effectiveness of the Landsat systems and to test the Geosat recommended supplemental space sensing capabilities. Such supplemental systems will be designed to optimally accomplish what can be done more effectively and economically by geological remote sensing from space.

V. NATIONAL NEEDS

Nationally, we are beginning to realize the seriousness of our country's growing shortages of non-renewable natural resources such as strategic minerals and energy sources like oil, gas, uranium, and coal. Social legislation, in particular with respect to environmental concerns, has materially increased resource development costs which in turn has domestically increased the economic "cut-off-grade" requirements (i.e., minimum economic risk percentage of metal content or minimum economic oil or gas deposit size) which thus has significantly reduced the probabilities of discoveries.

Because of these growing crises of the continual declining discovery rates for oil, gas, and strategic mineral deposits of the United States of America, the recommendations of The Geosat Workshop, held in Flagstaff, Arizona in May 1976, are being offered as supplemental space systems which potentially can increase the effectiveness of geological remote sensing from space for exploration and engineering. These capabilities include worldwide stereoscopic coverage in digital and film color and color IR format, radar, thermal IR, additional spectral bands, and in all cases high resolution to 10 meters, if possible.

In the final analysis, we firmly believe that the nation, as well as its exploration, engineering, and environmental geological industries should find increasingly invaluable and accordingly firmly embrace future applications of the present planned systems, as well as, geologically dedicated supplemental systems for geologic remote sensing of the earth from space. We believe this will assist in, at least, a partial solution to our declining domestic energy and mineral resource reserves. The Geosat Committee believes this to be urgent.

VI. ABSTRACT

Although the oil, gas, and mineral exploration in industry and environmental industries are the nation's largest single user group of satellite imagery, it still can be said that they are presently under-utilizing geological remote sensing from space. The geological industries rely on indispensable four-dimensional geological maps which are used by the geologist to interpret the subsurface existence of resource deposits before they are discovered.

In general, space sensors will not directly sense oil, gas, and mineral deposits or engineering and environmental geological problems. Thus, no bottom-line cost/benefits statement can be made as to how much oil, gas, and minerals will be found by space systems. But, present and planned NASA systems, as well as geologically dedicated supplemental systems can materially improve the process of making the requisite geological maps more efficiently and economically.

The geological industries have been historically slow to adapt to technologies, but they are rapidly beginning to use geological remote sensing from space. The addition of geologically dedicated supplemental systems to the planned NASA systems will encourage extensive utilization of geological remote sensing from space. As proof, The Geosat Committee, organized in 1976, is presently sponsored by 100 oil, gas, and minerals and engineering geology corporations to speak for the geological industries. Though recognizing that the long lead time from new sensor availability to new line or oil field development is a minimum of ten years, this Committee strongly endorses the Geosat Workshop recommendation for geologically dedicated supplemental space capabilities of world-wide film and digital stereoscopic coverage, radar, thermal IR, and additional spectral bands, all with up to ten meter resolution.

where feasible. The Geosat Committee believes; in light of the critical status of the remaining ten to fifteen years of oil and gas reserves, and fifteen to twenty years of strategic mineral reserves left in the United States; that the rapid addition of these supplemental geological space systems is urgent for our national needs

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METEOROLOGICAL SENSORS

AND

RELATED TECHNOLOGY FOR THE EIGHTIES

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ABSTRACT

This paper presents a brief overview of the sensors currently projected for the new generation of meteorological satellites which will be in operation during the First Global Atmospheric Research Program [GARP] Global Experiment (FGGE). The closely related subject of on-board data processing is treated briefly as well as efforts by the countries/agencies responsible for these satellites to make useful products available to developing countries at low cost.

1. INTRODUCTION

When space techniques began to be used for environmental sensing in the early 1960's, the only technology available was essentially based on developments which had been made for terrestrial applications. Hence the first meteorological satellites used television cameras to take "snapshots" of the earth's surface and atmosphere. During the sixties and early seventies, great strides were made in advancing the state-of-the-art, particularly in the sensor-related disciplines. This was largely because public interest in exploring this new frontier was at a level which permitted large amounts of money to be spent on research. Today, that public interest has waned to such an extent that NASA here in the United States, the European Space Agency (ESA) in Europe, and their counterparts in other parts of the world are struggling to maintain a viable posture in the face of severe competition for available money. The result is that the National Environmental Satellite Service, in preparing for the decade of the eighties is basing its plans, not only on "level funding", but on essentially "level technology". One should not conclude that we are going to stop improving the quality or quantity of the service we provide to our "customers." Whenever a new need is identified which can be adequately supported in terms of its benefit to mankind or more cost-effective operations, we will take steps to fill that need. We can look at this as a shift in emphasis from invention to ingenuity. We must try to close the gap between what our users want and what we are providing now not by expecting great breakthroughs but by clever applications of existing technology. Improvements may be accomplished by changes in the orbiting equipment or the ground processing. This paper will deal with the former, while John Leese's paper on Operational Data Processing addresses the latter.

2. HISTORICAL NOTES

It is appropriate to recall briefly just how far satellite meteorology has come. The first Meteorological Satellite, TIROS-1, was launched in 1960. Figure 1 shows a picture returned from one of its first orbits. The dark body of water is the Red Sea. In 1960, this and similar pictures, taken by television cameras on board the satellite caused great excitement and a new breed of meteorologist--the satellite meteorologist--began to come into existence. Over the ensuing years, many improvements and additions have been made. Resolution has

been improved, observations in parts of the electromagnetic spectrum other than the visible have been added, functions other than qualitative imaging are now performed (such as mapping of sea surface temperatures), and satellites have been placed in geostationary orbits to permit sequential viewing of a part of the earth's disk routinely every half-hour. Figure 2 shows an image taken by the Geostationary Operational Environmental Satellite, GOES-1, in the infra-red portion of the spectrum. Images like these are produced every half-hour by each of the two operational geostationary satellites operated by NESS. Another addition was the introduction of real-time transmission of images from the polar-orbiting satellites to relatively inexpensive ground stations around the world. This service, called Automatic Picture Transmission (APT), began with vidicon cameras and was continued when scanning radiometers replaced the television system. Figure 3 shows an image typical of that received by APT users from the NOAA-5 satellite currently in operation. The APT service is complemented by another direct, real-time transmission called High Resolution Picture Transmission (HRPT). This service, which is capable of much higher spatial resolution, is provided for users with more sophisticated receiving and display equipment. Finally, a service called WEFAX (Weather Facsimile) is provided to users within view of the U.S. geostationary satellites. This service disseminates products derived from both the polar- and geostationary-orbit satellites via the Applications Technology Satellites, ATS-1 and -3 in the VHF band and via the GOES satellites in S-band. The S-band service is a forerunner of the system to be incorporated by the world-wide network of geostationary meteorological satellites during the First GARP Global Experiment.

3. THE NEXT GENERATION

In an attempt to make the first comprehensive, world-wide observation of the earth's weather, the World Meteorological Organization (WMO) and the International Council of Scientific Unions (ICSU), as a part of their jointly sponsored Global Atmospheric Research Program (GARP), are planning the First GARP Global Experiment (FGGE). This massive data collection exercise will take place in 1978 and 1979 and will have as one key element the so-called Satellite Sub-System consisting of polar satellites launched by the United States and the USSR, plus five geostationary satellites launched by the US, the USSR, Japan, and the European Space Agency. It is beyond the scope of this paper to describe all of these satellites in detail, but some of the salient features deserve mention.

One characteristic of all satellite observing systems is their use of the electromagnetic spectrum to perform the task of remote sensing. Figure 4 depicts the parts of the spectrum used by sensors on past, present, and future satellites. Note that while TIROS used only the visible portion of the spectrum, the "second-generation" ITOS and GOES A, B, and C employ the infra-red for imaging and, in the case of ITOS, for sounding of temperatures. Sensors similar to those on ITOS are carried on the METEOR polar-orbiting satellites of the USSR.

In figure 4 the next generation of meteorological satellites is represented by the European METEOSAT, the Japanese GMS, and the United States TIROS-N and GOES D, E, and F*. Significant points of interest are the addition of a microwave sounder on TIROS-N and an infrared sounding capability on GOES, along with the METEOSAT capability for imaging in the 6.3 micrometer water vapor band. It should be noted that the additional capability on METEOSAT and GOES is considered experimental in nature. A decision to use the new data operationally will be made only after evaluation of early in-orbit results.

3.1 WORLD-WIDE CONTRIBUTIONS

Whereas the world's operational meteorological satellite systems are today provided by the USA and USSR, by the end of 1977 two new satellite operators will begin service to users. These are Japan and the European Space Agency which will launch geostationary meteorological satellites destined to support FGGE. Each satellite carries a spin-scan radiometer for imaging in the visible

*Note that GOES D, E, and F will not be launched for FGGE.

and infra-red, and a transponder for dissemination of data from the central processing facility to users within view of the satellite. In 1978, before the start of the FGGE, the USSR has announced it will launch a geostationary meteorological satellite. Each of these three satellites has certain new and unique features which will be evaluated during their early operation. The USSR spacecraft will be the first three-axis stabilized geostationary Metsat and will carry two redundant radiometers. The GMS will have fully redundant visible and infrared detectors and image processing electronics. METEOSAT, in addition to its 6.3 micrometer imaging capability, will perform a data processing function on-board.

The use of radiometers for imaging from spinning geostationary satellites, such as GOES, produces the undesired effect of generating a huge "burst" of data during the 5% of the time that the radiometer field-of-view sweeps across the earth's surface. This "burst" not only complicates the ground processing, it makes necessary the commitment of a correspondingly large block of the communications rf spectrum to the burst transmission which is only used for 30 milliseconds out of each 600 milliseconds. METEOSAT will store the "burst" of data on board the spacecraft and transmit it to the ground during the remaining 570 milliseconds, thus using significantly less rf spectrum and making possible less complex ground equipment. Users willing to accept unprocessed, non-gridded images can even receive the raw radiometer data directly with relatively inexpensive ground equipment during certain satellite operating modes.

In addition to those countries/agencies mentioned above, others are laying plans to experiment with satellite observations outside the FGGE time scale, but within the broad concept of GARP. India, for example, has requested proposals for a satellite (INSAT) which would carry a radiometer as part of a multidisciplinary payload also including telecommunications equipment. Although the operational future of the world-wide satellite sub-system is still uncertain, clearly the technological basis for such a global system will be firmly established in the 1980's.

3.2 THE UNITED STATES SATELLITES

The United States' contribution to FGGE will be its normal operational satellite system consisting of both geostationary and polar components. The next updating of the polar system has been timed to coincide with the beginning of FGGE. This updating will consist of the replacement of the current ITOS series by the TIROS-N series. The significant changes to be made for TIROS-N are (1) increase in atmospheric sounding capability, (2) increase of number of spectral intervals for multispectral imaging, (3) on-board processing to remove image distortion in the APT image, (4) a data collection and location system, and (5) increase in number of fully operational satellites from one to two.

3.2.1 SOUNDING. The increase in atmospheric sounding capability will be accomplished by the TIROS-N Operational Vertical Sounder (TOVS), which will have a total of 27 spectral channels. Table I summarizes the characteristics of the three main constituents of TOVS. The instrument represents significant increases from the current satellite system and provides for temperature, humidity and ozone measurements in the troposphere plus a microwave sub-system for obtaining data in the presence of clouds and stratospheric sounding using an instrument provided by the United Kingdom under a cooperative agreement.

TABLE I. TIROS-N OPERATIONAL VERTICAL SOUNDER
CHARACTERISTICS SUMMARY

Subsystem Characteristic	Stratospheric Subsystem*	Tropospheric Subsystem	Microwave Subsystem
Resolution at Nadir (km)	147	20	110
Field of view	10°	1.4°	7.5°
Spectral Regions used	15 μ m	15 μ m CO ₂ 11 μ m window 9.7 μ m Ozone 6.3 μ m H ₂ O 4.3 μ m CO ₂ 3.7 μ m window Visible	53 GHz Oxygen
Number of spectral channels	3	20	4
Range of Noise equivalent radiance (mW/m ² sr. cm ⁻¹)	0.125 - 0.625	0.001 - 0.750	(NEAT) 0.3°K

*provided by the United Kingdom

3.2.2 MULTISPECTRAL IMAGING. Although the present polar series carries a Very High Resolution Radiometer (VHRR) for imaging, the TIROS-N imager will incorporate new spectral channels. Table II gives the characteristics of the Advanced VHRR.

TABLE II. AVHRR CHARACTERISTICS

Channel	Resolution (nadir)	Wavelength (μ m)	Use
1	1 km	0.55 - 0.9	daytime cloud and surface mapping
2	1 km	0.725 - 1.0+	surface water delineation
3	1 km	10.5 - 11.5	SST, day/night mapping
4	1 km	3.55 - 3.93	SST
5*	1 km	11.5 - 12.5	SST

*Channel 5 will not be included on early flights, but will be added later to further enhance Sea Surface Temperature (SST) measurements in the tropics.

3.2.3 ON-BOARD PROCESSING. One of the significant improvements for TIROS-N will be the on-board processing to remove the foreshortening inherent in imaging with a scanning radiometer whose scan mirror turns at a constant angular velocity. This distortion has been present in the APT images produced by the ITOS series of satellites. On TIROS-N, the on-board computer will use the high resolution AVHRR data to produce a synthesized low-resolution image. Figure 5 is the image as produced by the AVHRR. Figure 6 is the synthesized image after processing. Note the removal of most of the foreshortening distortion.

3.2.4 DATA COLLECTION AND LOCATION. For the first time on a polar satellite, the TIROS-N will operationally interrogate, collect data from, and locate data collection platforms; thus permitting the gathering of data from in-situ sensors in addition to the remote sensors on board. This system, called ARGOS, is being provided by France.

3.2.5 GEOSTATIONARY IMPROVEMENTS. The next updating of the United States' geostationary environmental satellites will not take place until after FGGE. Nevertheless, the sensors for this satellite series are already under development. The current sensor, called the Visible and Infra-red Spin-Scan Radiometer (VISSR) produces images such as those in figure 2. This capability will be maintained on future spacecraft, but an additional capability will be included. The sensor being developed is called the VISSR Atmospheric Sounder (VAS) and provides the capability for multispectral imaging and sounding. The usefulness of the data will be evaluated after launch of the first GOES spacecraft equipped with VAS. If operational viability is established, this new sensor could be helping provide better knowledge of mesoscale phenomena by the latter half of the 1980's.

4. CONCLUSION

In the introduction, it was stated that no new "breakthroughs" in technology are being anticipated for the sensors of the 1980's. Nevertheless, the author has tried to show that the possibilities for improvements in quality and quantity of satellite derived products through improved sensors and on-board processing remain great. The challenge of the Eighties is to make better uses of the technology extant.

ACKNOWLEDGEMENTS

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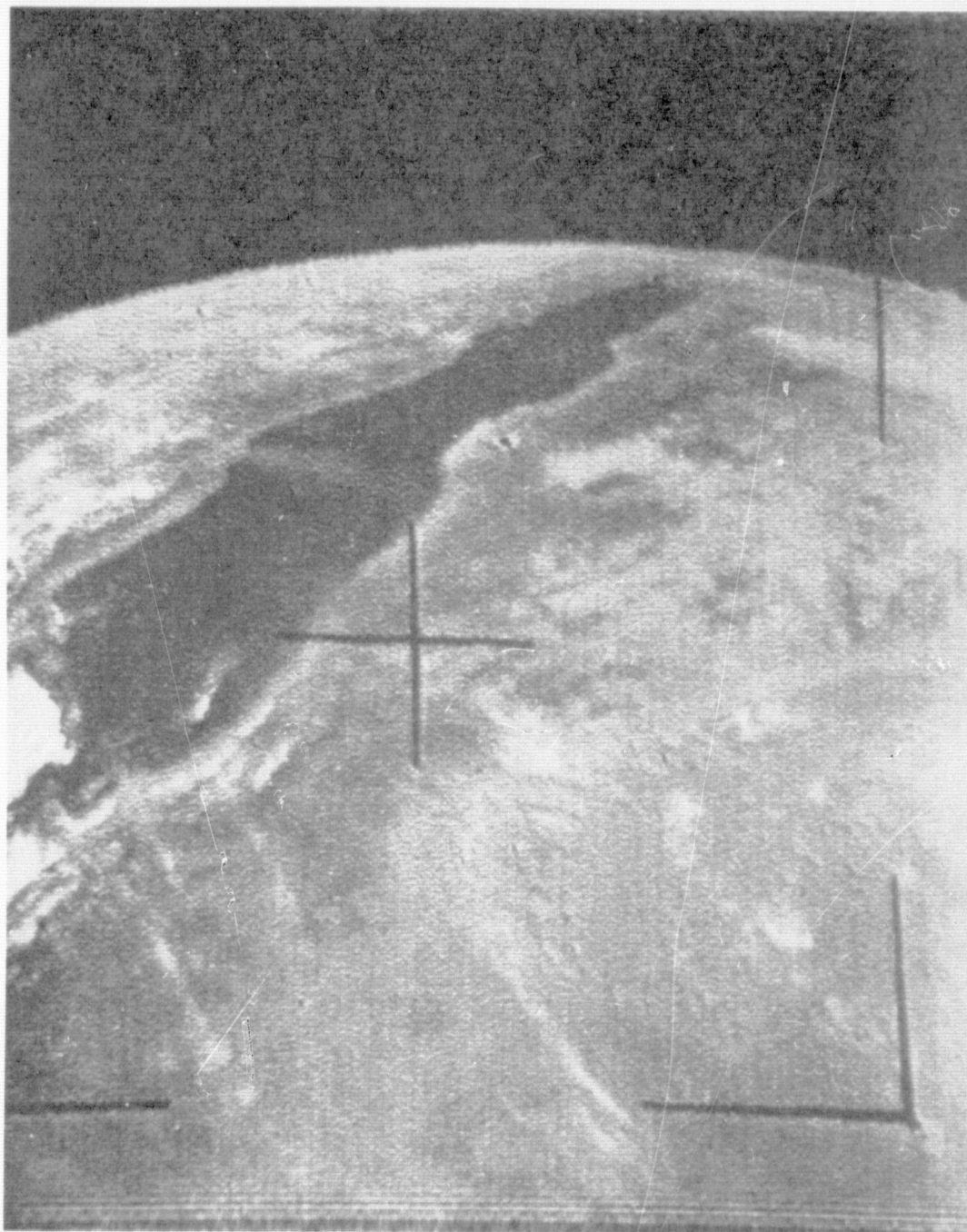


FIGURE 1. IMAGE PRODUCED BY TIROS 1. The dark area is the Red Sea. Black lines are "fiducial marks" etched on the face of the television camera's vidicon.

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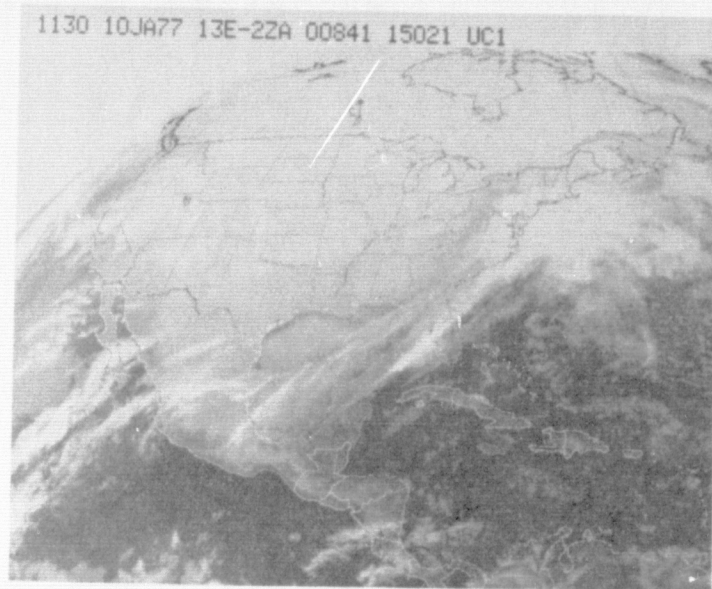


FIGURE 2. IMAGE OF THE NORTH AMERICAN CONTINENT FROM GOES-1. The image is produced from infra-red sensor data. Cooler objects appear white and warmer objects appear dark.

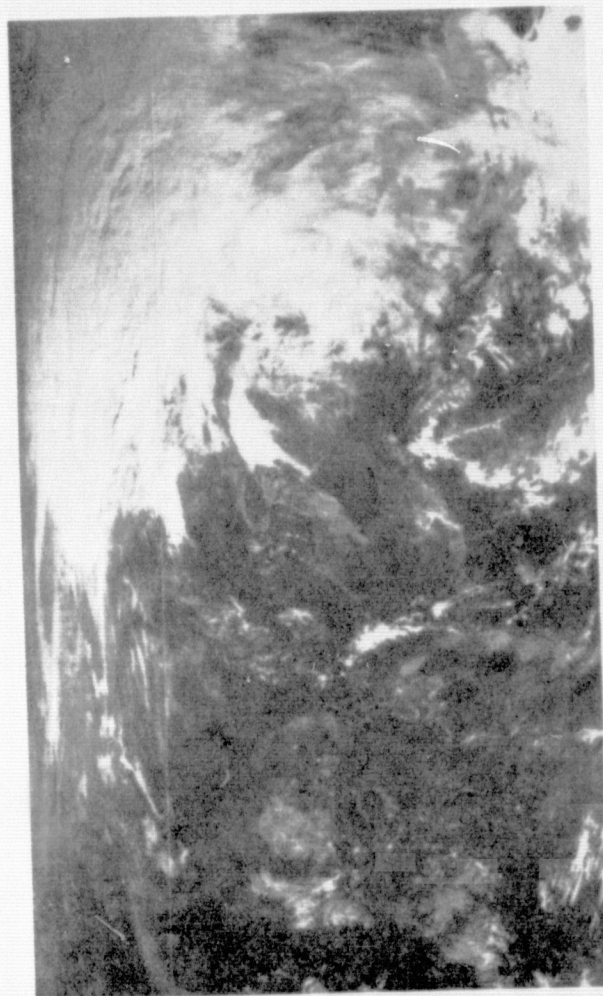


FIGURE 3. APT-TYPE IMAGE. This picture is typical of the images received by means of the real-time transmission from NOAA-5. The Florida and Yucatan peninsulas are visible near the center of the picture.

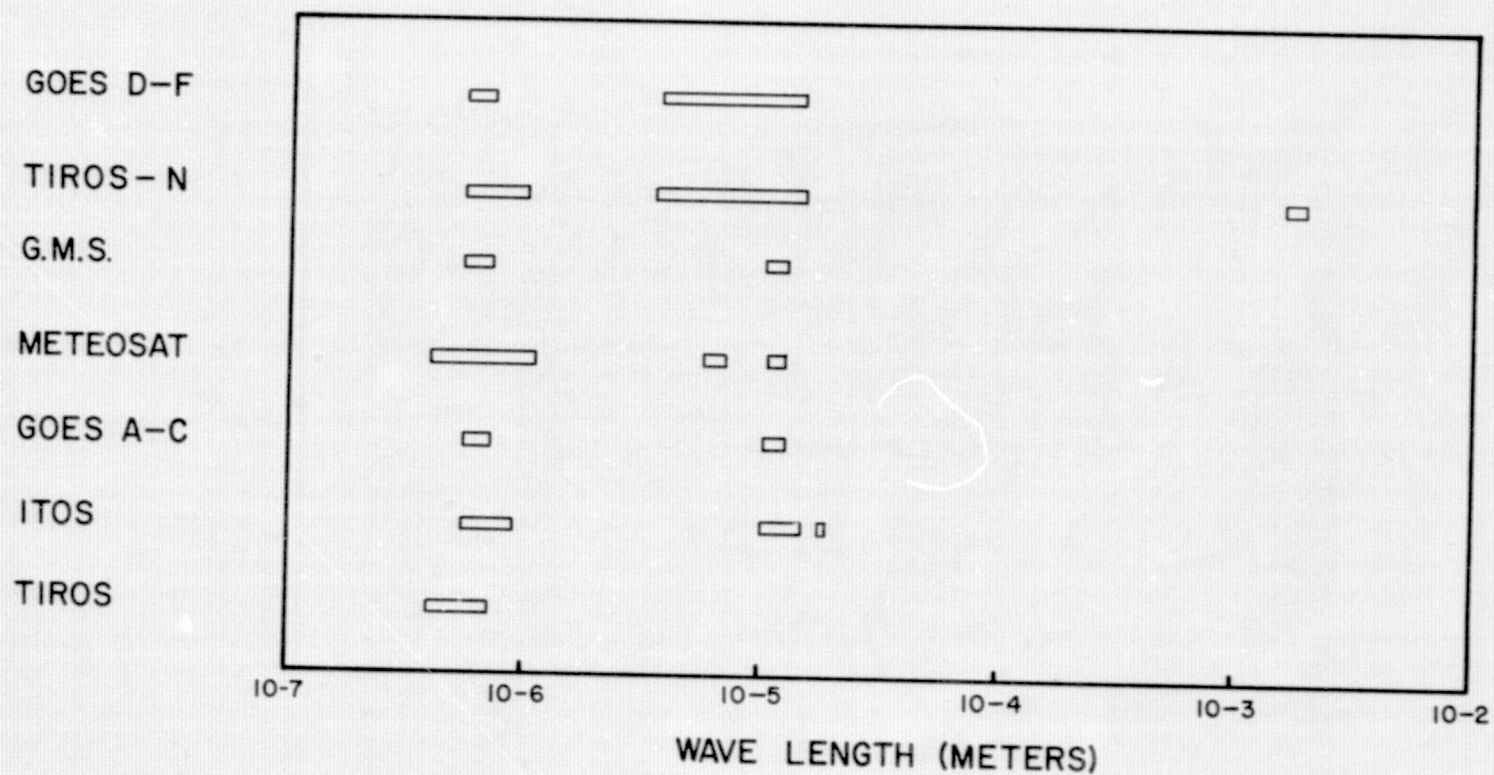


FIGURE 4
USE OF SPECTRUM BY
SENSORS ON VARIOUS
SATELLITES.

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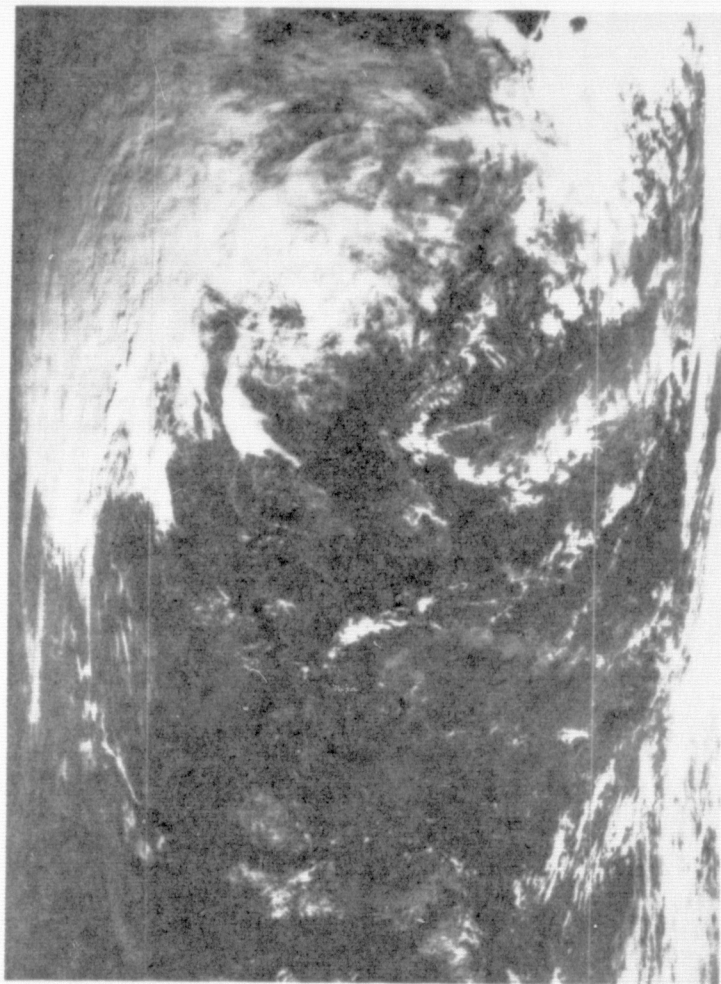


FIGURE 5. ORIGINAL IMAGE. High resolution image
produced by TIROS-N AVHRR.

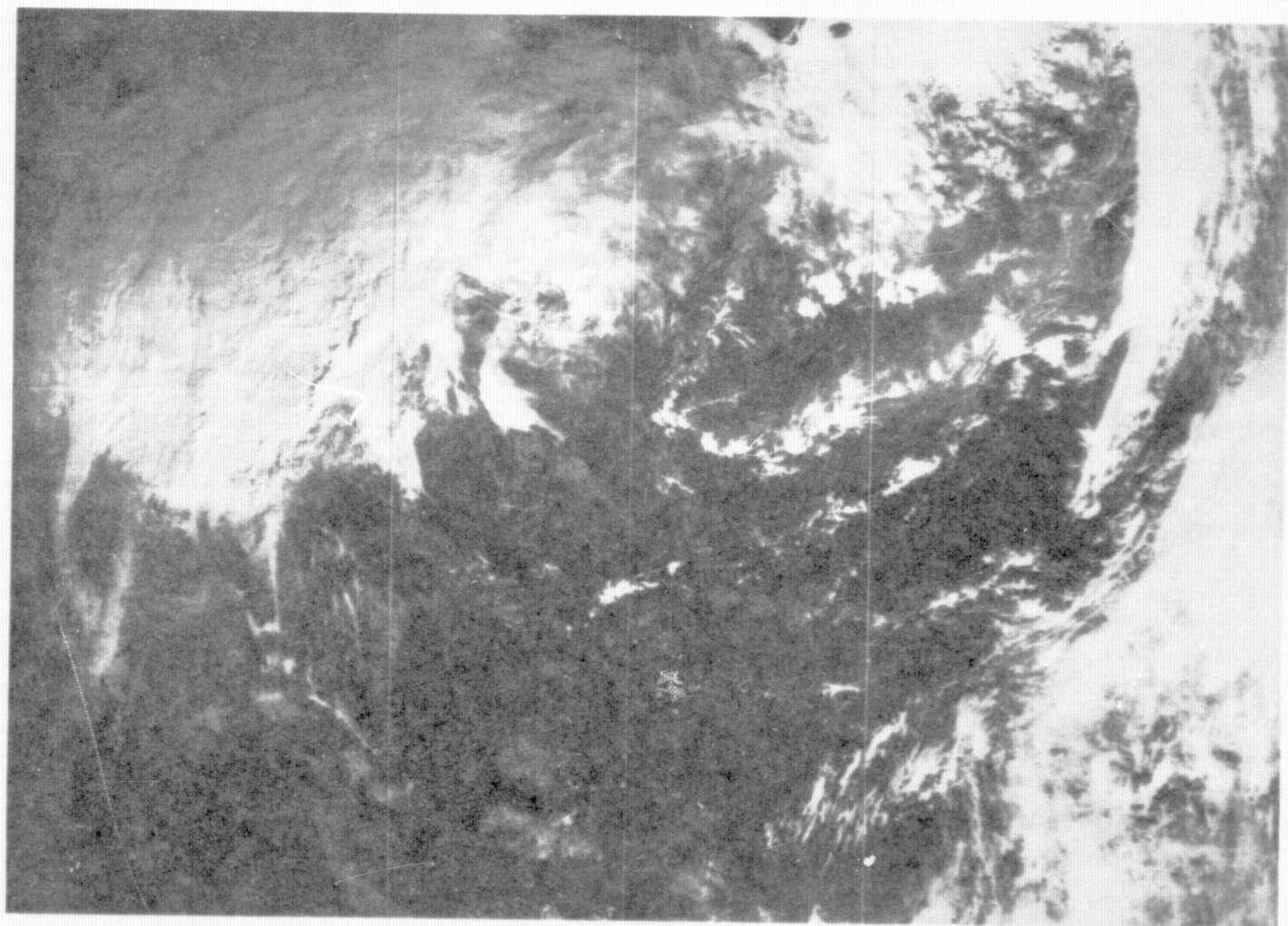


FIGURE 6. PROCESSED IMAGE. Note removal of most foreshortening distortion with respect to Figure 5.

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OPERATIONAL DATA PROCESSING -

The First Ten Years are the Hardest

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ABSTRACT

The subject of data processing in the Proceedings of a Remote Sensing Symposium should logically be directed toward the output products derived from an input of remotely sensed data. There are a number of other papers in these Proceedings (see list at the end of this paper) which deal with the derivation of specific environmental parameters from the operational environmental satellite system. We have taken the opportunity to write a review of operational data processing with emphasis on its evolutionary development in the National Environmental Satellite Service. We chose to provide a general review as a time sequence of events to establish a perspective for the current operations and where we see it headed in the future.

THE EXPLORATORY YEARS

Interest in meteorological satellites really began with cloud pictures from cameras carried on war surplus rockets and by the mid fifties, the late Harry Wexler was looking at a cloud picture mosaic from an Aerobee rocket (Hubert, 1955). Before the USSR's first Sputnik in October 1957, he was visualizing a global cloud picture which would fill in the weather details implied by the Norwegian Polar Front Theory (Wexler, 1954).

With the launch of TIROS-1 seventeen years ago, Dr. S. Fritz had assembled a small Weather Bureau staff to explore the value of satellite cloud pictures in support of weather analysis and prediction. Anticipating an image Earth location problem, he had organized a small computer support group which subsequently evolved into today's substantial data processing operation. In those first exploratory years many problems were addressed, and the resulting insight provided a foundation for the ten years of operations to be recounted in this overview paper.

As some will recall, the early TIROS (Television-InfraRed Observation Satellite) spacecraft were spin stabilized with vidicon cameras looking out one end along the spin axis. With the spin axis in the orbital plane, this meant that the cameras saw the earth for only a portion of each orbital pass (see early summary paper by Fritz, 1964). The overlapping image sequences, with foreshortening varying from horizon scenes to nadir scenes, greatly complicated the interpreters task. Familiar landmass features were often strangely deformed. The interpreter's nephanalysis first required the careful mosaicing of images into scene strips and then the tedious transcribing of pertinent cloud features from the variably distorted scene onto a standard weather map projection as shown in Figure 1. The obvious first need was for latitude-longitude image locator grids, and much of the early processing effort was devoted to this requirement. Interaction with users produced a hierarchy of locator grids.

¹ C.L. Bristor is retired from the National Environmental Satellite Service and is now working as a Certified Consulting Meteorologist.

Transparent overlays were produced from computer driven line plotters, and the process was later speeded up by using computer output to drive a graphic microfilm recorder. As the exploratory operation became more routine, grid fit deficiencies became more important. Users became more skilled in the melding process and applications became more sensitive to errors in Earth location. As coastlines, rivers and other physiographic features were incorporated in the grids, any mismatch with satellite imagery was immediately apparent. In seeking improvement in gridding precision, the computer support group pursued several investigative tasks. Diagnostic tests were devised to check the validity of orbital elements derived from tracking station data, and exploratory efforts were directed toward attitude determination using horizon and picture landmark control point information.

During this period computer support was largely a reaction to problems encountered by analysts and research personnel who were spending an inordinate amount of time in the locator melding process. The real solution, however, was not to improve the hand tools but rather to automate the melding process and eliminate the waste in analyst resources. This came with the experimental activities in the TIROS Operational System (TOS).

EXPERIMENTAL OPERATIONS

Despite the limitations of the TIROS early exploratory effort, the potential value of cloud imagery in weather analysis and prediction was evident, and, with TOS, daily global coverage was achieved. The basic spacecraft was retained, but, with camera and horizon trigger mounted on the spinning cylinder's rim, nadir views were obtained as the satellite rolled along its orbital track. The resulting global coverage with essentially invariant distortion patterns, coupled with newly acquired large scale computing support, opened the way for a greatly expanded data processing operation. Facilities were designed and installed so as to provide for quick look analog image prints as well as for the computer manipulation of digital image data.

The main features of the TOS central processing system are shown in Figure 2. A hybrid microfilm display device was used for the gridding operation in which incoming analog video signals were combined on film with pre-calculated Earth locator grids. An example of this process is shown in Figure 3. Frame synchronization signals started the device in a line-by-line open shutter exposure of the film as the incoming signal modulated the recording light beam. At frame termination, control was automatically transferred to the contents of a computer generated digital tape. Commands and data from this tape directed the generation of label characters and grid lines after which the camera shutter closed, film advanced, and the device awaited the next frame synchronization start pulse. Throughout the late sixties, many thousands of gridded vidicon images were produced by this device.

Although automatic grid melding simplified nephanalysis operations, it did little to broaden the information extraction opportunities. Gridded vidicon strips from one day to the next could not be conveniently juxtaposed for time trend comparisons or used in direct overlay comparisons with other coincident weather data on standard maps. Therefore, in parallel with continued support for hand interpretation efforts, software was developed by which digitized image data were transformed into global mapped mosaics. The line and sample coordinates of incoming picture elements were transformed, using orbit and attitude information, into latitude, longitude equivalents and then into square i, j fine mesh coordinates overlayed on either polar stereographic or Mercator maps (Bristor et al., 1966). A five year record of such mapped vidicon data was produced as a routine daily activity. A typical example is shown in Figure 4.

The years of TOS operations are best described as a period of experimentation. Early image mapping software was converted from the IBM 7094 to run on the CDC 6600. Critical core program segments were optimally coded in assembly

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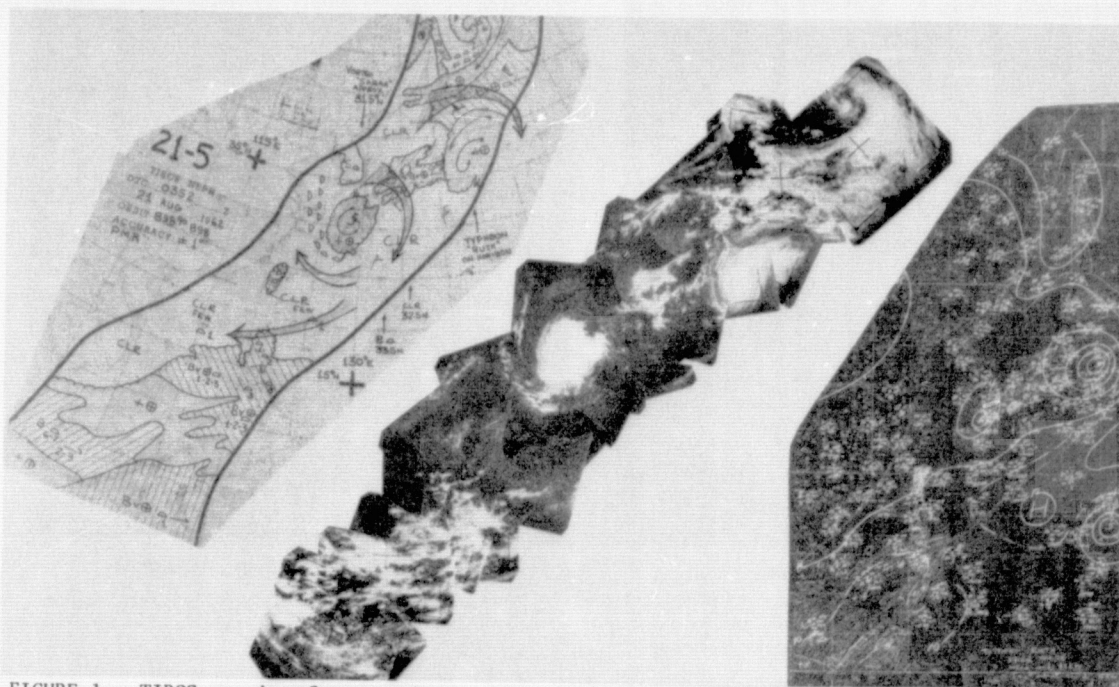


FIGURE 1. TIROS mosaic of twenty images with resulting nephelanalysis (left) and concurrent weather chart. Typhoons Ruth (center) and Sarah (below) are both shown in this 1962 mosaic.

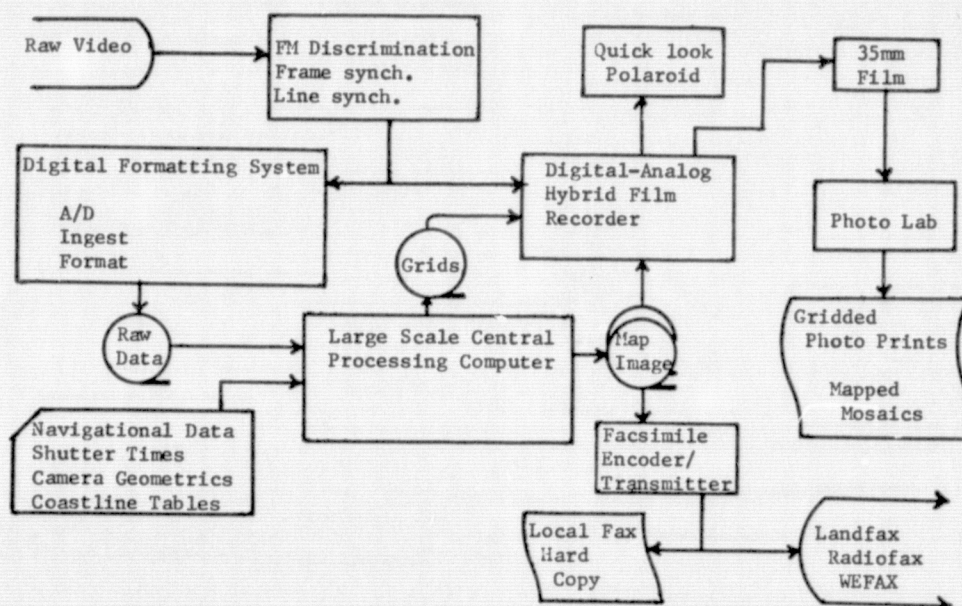


FIGURE 2. TOS Central Data Processing Operation. Starting with ESSA-3, all centrally processed Advanced Vidicon Camera System (AVCS) images passed through this system. Gridded photo prints were first produced followed by mapped mosaics.

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FIGURE 3. TOS vidicon image with locator grid and labels automatically implanted. Approximately one half million images from TOS underwent such central processing.

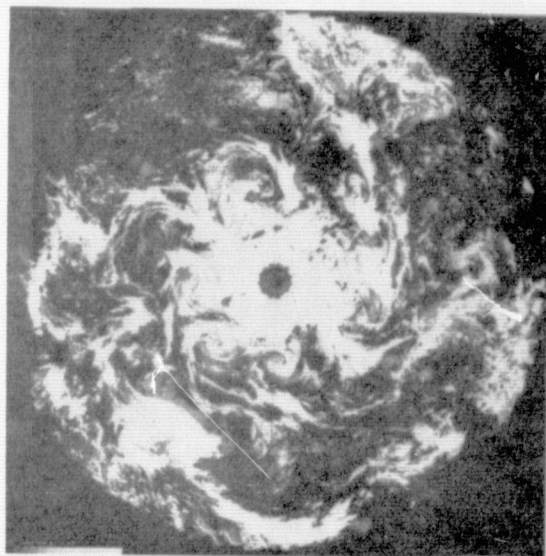
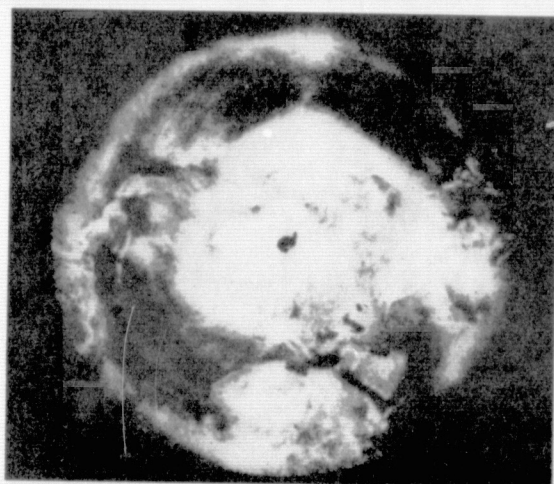


FIGURE 4. Polar stereographic mapped vidicon mosaic.



MEAN TOTAL CLOUD AMOUNT (Octas) JUNE 1968
BLACK=CLEAR - WHITE = 8/8 BACKGROUND INCLUDED

FIGURE 5. Mean monthly cloud cover chart. Each element of the 512x512 array expressed cloud amount for a 64 element sector (white is overcast, black is clear).

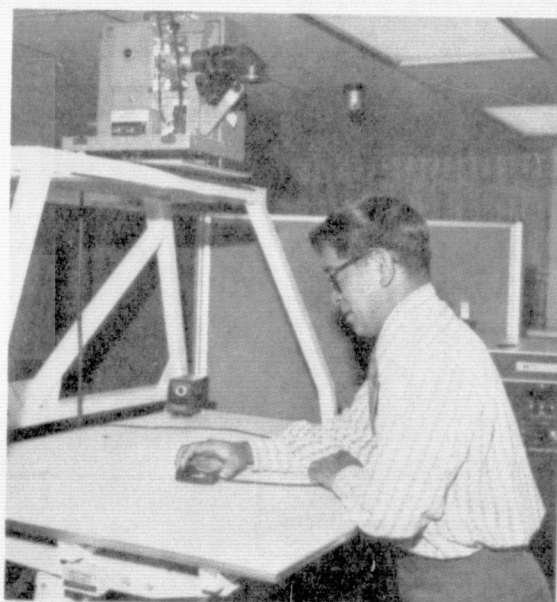


FIGURE 6. The vector end point extraction station consists of the loop movie projector and the Bendix "Datagrid" Digitizer. Not shown is the attached IBM 029 card punch which provides output.

language, and options were added to permit sector mapping at higher resolution. This added flexibility provided opportunity for several applications experiments, and substantial computer resources were soon committed to daily production. Once global image mapping was stabilized, attempts were made to summarize the 4096x4096 polar hemispheric arrays into a data base for other uses. After some experimentation, sequences of daily tape files were created in which brightness distributions for 8x8 sample clusters were recorded in five response ranges. This data base production continued until the end of the TOS program, and it provided the input for a four year Atlas of Relative Cloud Cover (Miller, 1971). A contoured image from such summary data is shown in Figure 5.

In order to assist those engaged in snow and ice studies, sequences of daily mapped mosaics were combined to remove transient cloud obscuration. Using five day clusters, only the minimum brightness value was recorded for each mapped image element position. The resulting composite minimum brightness image revealed the edges of snow and ice fields with little remaining cloud contamination. Such charts proved of value in several investigations (McClain and Baker, 1969). During spring thaw flood threat situations, limited tests were conducted to investigate the feasibility of measuring snow melt using sequences of composite charts.

Apart from applications experimentation, operating system flaws and processing problems prompted several diagnostic investigations. Pre-launch calibration images of polar targets and others of controlled light sources provided inputs for geometric calibration and for brightness normalization. However, post-launch changes were to be expected, and monitoring efforts uncovered need for both hardware and software alterations. Variation in frame synchronizing signals between vidicons required more sophistication in hardware detection circuitry, and noted variations in frame-to-frame raster linearity led to a software investigation in which line and sample coordinates of fixed camera fiducial marks were found to meander in a spiral pattern through an orbital imaging sequence. In addition to such concern for geometric stability, aging changes were noted in the brightness response of cameras and associated circuitry. This prompted production of a response summary punch card for each image frame. By appropriate analysis of such records, response trends could be tracked and compensating corrections made in normalization lookup tables.

While efforts were being made to develop applications and stabilize TOS operations, the launch of NASA's first geostationary Applications Technology Satellite (ATS) provided new opportunity for experimentation. A spin scan imaging telescope had been included as a result of the innovative efforts of Professor V.E. Suomi and his colleagues at the University of Wisconsin. Initial struggles to utilize the data somewhat paralleled the beginning TIROS effort. Earlier software was modified to produce overlay grids and the hand melding process revealed the need for more precision in navigational inputs. Again, horizon and landmark control points were used, and the several experimenting groups soon devised acceptable attitude determination procedures. With help from Professor T.J. Fujita's group at the University of Chicago, a variety of experiments went forward in which sequences of images were examined as lapse time movie animations. All were impressed with the possibility of using moving clouds as indicators of atmospheric motion, and by 1969 the extraction of cloud motion wind estimates had become a routine operation. Young et al., 1972, described the steps in this computer assisted manual effort, and a view of some of the operating equipment is provided in Figure 6.

Apart from animation, ATS also provided broadscale coverage as opposed to repeated two hour time slippages obtained with strip mosaics from TOS. Since weather analysts are interested in broad synoptic comparisons, mapping codes were revised to produce both polar stereographic and Mercator ATS imagery. Such transformations were produced using ATS-1 data and later also

data from ATS-3. Production continued until operations were moved from the CDC 6600 to larger facilities.

ATS operations also required diagnostic monitoring efforts. Daily histograms from digitized images were analyzed and trend curves were plotted to assure stability in discriminator setting and proper digitizer performance. Scan line amplitude profile graphic plots also provided insight concerning noise content and signal clipping. The degree of fit between coastal map outline features and the corresponding image features provided the best evidence of the accuracy in the Earth location processing.

Many lessons were learned during these early operations with TOS and ATS. Apart from user pressures for more and improved sensors which led to ITOS (the Improved TOS series), the data processing experiences provided insight toward an improved ground processing system. It also made evident the need for more supportive processing resources. Specifically, the need was indicated for constant monitoring of incoming raw signals in the most quantitative way possible. It also indicated the importance of a proper technical staff to maintain and validate the specialized ingest, display and other dedicated equipment.

A variety of factors encountered in this early experience also pointed to the additional need for a software support team to assist in devising diagnostic troubleshooting routines and to maintain operational software. Among these factors are items such as periodic changes in large computer system software which often require user changes, navigational software requiring occasional replacement of Ephemerides tables, image data calibration and normalization routines which may require lookup table alterations, changes linked to hardware modification, and software alterations to improve running efficiency or to modify production output.

Finally, there is need for an organized effort to check the timeliness and validity of output products. Such a quality assurance group must possess a diversity of talents so as to understand both hardware and software problems and so assist under anomalous circumstances to minimize the impact on production. Further detail concerning processing and output applications has been provided by Leese et al., (1970).

INITIAL QUANTITATIVE OPERATIONS

Data from scanning radiometers became part of the operational system in 1970. Beginning with ITOS-1, launched January 23, 1970, satellites of this series (ITOS-1, NOAA-1 through NOAA-5) have provided routine measurements from a two channel scanning radiometer (0.5 to 0.7 micrometers and 10.5 to 12.5 micrometers) with a ground resolution of approximately 8 km. at the satellite subpoint.

Beginning with NOAA-2, launched on October 16, 1972, a Vertical Temperature Profile Radiometer (VTPR) has been providing remotely sensed measurements from which atmospheric temperature profiles can be derived. The VTPR has six discrete channels within the the 15- micrometer carbon dioxide absorption region, one in the 11- micrometer atmospheric "window" region, and one in the 18- micrometer water vapor absorption region of the infrared absorption spectrum.

Data from the GOES (Geostationary Operational Environmental Satellite) also provided routine measurements from a two channel scanning radiometer beginning in May 1974. The Visible and Infrared Spin Scan Radiometer (VISSR) provides Visible data in the 0.55 to 0.75 micrometer range at a ground resolution of about 1 km. and IR data in the 10.5 to 12.6 micrometer range at a ground resolution of about 8 km.

Further details on the ITOS and GOES satellites and the sensors used on these spacecraft are given in other papers by NESS authors in these Proceedings. A listing of these papers is given at the end of this paper. A description of the operation of the NOAA Polar Satellite System is given by Fortuna and Hambrick (1974), and ITOS products are summarized by Hoppe and Ruiz (1974). Bristor (1975) provides a detailed description of the GOES satellite together with specific descriptions of the central processing and analysis of the data received from these satellites.

NESS personnel entered the decade of the 1970's with confidence and enthusiasm about the ability to achieve quantitative information from the operational environmental satellite data to be available during this period. The two authors of this paper were among the most confident and most enthusiastic at the beginning of this period. After seven years of struggle with less than total success on the objectives initially set we both maintain a high degree of confidence and enthusiasm for working toward the goal of quantitative information.

Three major processing models were developed and implemented as part of the operational data processing in NESS during the period 1970-72. These models were:

- GOSSTCOMP (Global Operational Sea Surface Temperature COMputation) which provides a daily global surveillance of the ocean's surface temperature structure.
- Picture Pair is an automated model for measuring cloud motion vectors using pairs of geostationary satellite images.
- VTPR Processing is a series of processing routines which provide twice daily measurements of atmospheric temperature profiles over the ocean areas of the globe.

Each of these models and the results are described in some detail in other papers by NESS authors in these Proceedings and will not be repeated in this paper. A review of some of the major similarities and differences among the three models will serve to illustrate the general principles and objectives of the quantitative processing done at the National Environmental Satellite Service.

Each of the models was initially designed to be as automated as possible. This was especially true for the early processing steps because early flaw detection with large data rates avoids waste in processor resources. Each of the models contained the basic components of an automated operational procedure. This must include a valid measurement technique, the ability to perform quality control and noise contamination measurements on the raw data, detection of valid areas for making measurements, and the exercise of quality control procedures over the numerical values obtained from the measurement process.

Hindsight indicates that the work to develop operational procedures to derive sea surface temperatures and satellite winds placed too much emphasis on the measurement techniques at the expense of other portions of the model. Work on techniques for the computer measurement of satellite winds during the period 1967-72 was highly concentrated on developing the most efficient and reliable technique. By late 1971 it became clear to the authors that the specific measurement technique was not as critical as it appeared earlier. Further discussion of this evolutionary development is given in Leese et al., 1970b and Leese et al., 1971a.

The work to date on computer techniques for deriving sea surface temperature observations has relied on a combined detection and measurement unit. The ability to eliminate cloud contamination was thought to be the most

significant factor in determining the eventual accuracy of the derived sea surface temperature values. As a result of this belief nearly all of the early effort during the period 1969-73 was devoted to developing the most efficient and reliable method of measuring the surface clear radiance value. By the middle of 1973 it became very clear that the variability in atmospheric moisture attenuation was a severe problem. It was also very clear that the accuracy of the sea surface temperature value was heavily dependent on many parameters other than cloud contamination. These include atmospheric moisture attenuation, Earth location accuracy, and noise in the satellite and ground data acquisition subsystems.

Considerable effort has been expended on detecting valid areas for making measurements. The subject of target selection for making valid cloud motion measurements was one of much discussion and debate between those who argued for a manual mode versus those who believed it could be completely automated. In late 1971 we made a decision to use a fixed grid to make measurements in an operational mode, and thus reduced the problem to that of computer costs (Bradford et al., 1972). As a result we found it was less costly to make computer measurements at all locations and depend on a post editing process to delete bad measurements rather than expend the effort to analyze the target prior to making the measurement. Since we were measuring low level cloud motion vectors over ocean areas, this decision may not apply to more complex multi-layer cloud tracking tasks. The availability of thermal IR data has enabled us to implement temperature slicing as a simple target analyzer. This has improved our ability to make low level cloud motion measurements closer to storm systems and thus add significant information to the set of vectors derived.

We recognized the need to exercise quality control over the incoming data and the numerical values obtained from the measurement process. A review of the technical papers describing the early operational models (Leese et al., 1971b, and McMillin et al., 1973) indicates that we had very little appreciation for the scope of quality control procedures needed to sustain an operation for quantitative processing. A common weakness in all three models, at the beginning of operations, was the on-line data quality diagnostics. The quality control checks were primarily designed to reject the output products to avoid sending bad information to the users. We could identify that something was wrong in the system but we lacked the diagnostics to identify where the problem was occurring. Searching for a problem somewhere between the spacecraft sensor and the output product from the operational processing consumed many manhours by involving operational and maintenance specialists in all portions of the data acquisition and processing system. The futility of this approach to problem solving became very clear in trying to diagnose data quality problems in the ITOS scanning radiometer data. A very sophisticated system of redundancy was designed into the sensors, spacecraft, and ground data handling system to achieve a high degree of reliability in an operational mode. It was found that the scanning radiometer data could take any one of 512 possible paths between the sensor on the spacecraft and the computer system used for the operational data processing. It was also found that many of these paths were exercised on a once per month basis to check their suitability for operations in case of need. We chose to reduce these problems to a manageable size by designating a single path for the operational data flow and changing the path only when it was necessary due to a component failure in the system. We also decided not to switch sensors on a monthly basis but rather to select one sensor as the primary and operate it until it failed, and then switch to the back-up sensor. A very sophisticated quality control program was implemented in 1972 to critically evaluate the scanning radiometer data for its suitability for quantitative processing. Thirty five parameters are examined within each frame of 25 scan lines to ascertain data quality. All 35 parameters are compared to minimum and maximum threshold values established for each parameter. Orbital summaries are produced as a quality control tool by on-line monitoring personnel. This diagnostic package also generates messages when problems are detected to assist the operational personnel in diagnosing where in the system

the problem is occurring. Quality control of the output products from the GOSSTCOMP and VTPR Processing have relied very heavily on automated procedures. These automated procedures have placed a heavy reliance on "first-guess" information to establish thresholds of acceptability for the product. The GOSSTCOMP made use of limits for the deviation from yesterday's analysis as thresholds for accepting today's observations. This placed severe limits on the model's ability to detect and measure areas of sudden cooling or warming. The VTPR Processing used forecasts from the Numerical Weather Prediction model to establish limits and made decisions about accepting or rejecting a specific atmospheric temperature profile measurement. Both of these suffered the drawback of providing feedback to the operational system which could cause the operational processing to go unstable. For example, if yesterday's sea surface temperature analysis inadvertently accepted bad observations into the analysis field in a certain area of the ocean, it may not be possible to accept good observations from today's processing output because the thresholds for acceptance are so heavily based on yesterday's values. This weakness in the product quality control has been removed from both the GOSSTCOMP and the VTPR Processing.

Picture Pair processing has always relied on manual editing as the final step in the processing, and thus the man makes the final decision on accepting or rejecting a specific satellite wind observation. The manual editing has made a sizable contribution to the stability and reliability of the satellite wind products during the five-year history of the picture pair processing.

The lack of suitable ground truth information has been a severe hindrance to the development of quantitative processing techniques. GOSSTCOMP output is measured against conventional measurements of sea surface temperature made by ships. The latter represents a bulk measurement of temperature whereas the satellite derived values represent "skin" temperature measurements. VTPR Processing uses rawinsonde measurements to evaluate the quality of the satellite derived atmospheric temperature profile. The rawinsonde represents an in situ point measurement as the sensor is carried vertically into the atmosphere by a rising balloon. The satellite derived profile represents an average value over a relatively large volume of the atmosphere. Picture Pair processing uses the wind vectors determined from the rawinsonde processing as a measure of the quality of the satellite winds derived from cloud motion vectors. Here again, point measurements of the rawinsonde are used to evaluate the satellite wind which represents the average motion of a cloud volume over a 30- or 60- minute time span.

The introduction of quantitative processing as part of the operational satellite data processing represents a very exciting and challenging period to the authors of this paper. The total expectations which we held in 1970 for this new area are not yet achieved and present some very challenging technical problems for future work. The year 1973 represents strong memories in our experiences with operational processing of satellite data. At this time the three CDC 6600 computers in the NOAA Central Computer Facility were replaced by IBM S360/195 systems. The conversion of the operational computer programs started in the spring of 1973 and did not get completed until the summer of 1974. The total conversion process for the satellite data processing cost approximately 50 man years of effort.

Operational satellite data processing has experienced the same type of growing pains that other on-line computer applications have experienced. The pressure to implement an operational system as rapidly as possible forced shortcuts in the design and development phases. Many studies have been conducted on the problems of computer software development and maintenance. These studies have identified a series of stages which a computer software project goes through. The authors' experience in operational satellite data processing during the early 1970's led us to conclude that each project went through similar stages which might be generalized as follows:

Stage 1 - Development and Early Experimental Operations. This stage was characterized by a high degree of optimism and a flurry of activity. It was also marked by the fact that all the designers and developers were involved in the early operations to keep it going. These same people were "nursing" the processing so that problems did not get the full opportunity to surface.

Stage 2 - Operations and True Problem Definition. This stage began when some or all of the designers and developers quit performing on the project and moved into other areas. The model finally got a chance to show how it really performed in its advertised "automated" mode. Quick fixes became the modus operandi with new problems occurring at least as fast as old ones could be solved. A characteristic of this stage was frustrating hectic activity with exclamations such as "We can't go on like this forever!" "The more we learn the less we know!"

Stage 3 - Problem Solving. In this stage the more senior people on the project began to examine the overall problem in a systematic manner. Gaining sweeping improvements by a single change in the processing was no longer touted as a viable approach. Paper designs were taken through a "scenario of operations" before the first line of computer code was written. The current operational model ran in a reasonably stable manner with the output well below initial expectations. In this final stage, people on the project began to turn optimistic again when they recognized it was possible to meet the objectives originally set out for the project; it was just that it was probably going to take at least 10 times longer to achieve them all than was originally projected.

1975-79 DATA PROCESSING MATURES

The techniques used to develop and implement computer software up through the mid-1970's resulted in a very heavy workload for software maintenance during the operational phase. By the end of 1975 the National Environmental Satellite Service had about 70% of its data processing expertise devoted to maintenance activities in the operational data processing. The need to use such highly talented resources in operational maintenance combined with the level funding for environmental satellite programs in the NOAA brought the problem to the forefront in 1976. Data Processing studies were conducted in the operational data processing facility to determine how the NESS should operate in a computer technology environment where the computer hardware costs were continuing to decrease while the computer software costs were continuing to increase. Three concepts for changes in our data processing environment have evolved from this review:

- (1) Life-Cycle Management for ADP Systems.
- (2) Data Base Management Concepts for handling remotely sensed data and products.
- (3) Centralized Automated Library Management System (CALMS) for operational software.

The concept of Life-Cycle Management for ADP Systems forces us to consider all costs from the inception of an idea through the termination of an operation. We have identified six stages in the life-cycle for operational data processing:

- Mission and User Requirements
- Analysis
- Design
- Implementation
- Maintenance
- Termination

We believe that this process will raise the priority and increase management's attention to the operations and maintenance costs at the beginning of a project

when it is possible to make tradeoffs to achieve a goal of minimum cumulative costs over the life of a system.

The use of Data Base Management Concepts provides the opportunity for more functional specialization in the operational data processing system. It also affords the opportunity to implement data standards and checkpoints at strategic points in the operational production flow. This reduces the amount of time needed to find and diagnose problems in the system when they occur with a resultant reduction in maintenance costs.

The use of a Centralized Automated Library Management System (CALMS) reduces the number of persons involved in keeping track of the operational software. It also provides the opportunity to implement software standards for the operational data processing facility. The use of standards in computer programming makes the software more readily understandable to persons other than the one who coded it originally. These techniques also provide the opportunity for more functional specialization in the operation and maintenance of the operational data processing system.

Current Operations - We currently process the data from one ITOS type (NOAA-5) polar satellite and two geostationary satellites. During the past year we have made a concerted effort to place the operational processing of the ITOS data into a steady state condition. We have shifted nearly all the development resources to the design, development and implementation of the third generation polar satellite system (TIROS-N).

The GOES satellite data processing has made some significant advances during the past two years. The NESS began its own operations for orbital determination and prediction in early 1976. For all previous NESS operations, satellite position determination support has been provided by the NASA Space Tracking and Data Acquisition Network (STADAN). Orbit determination is performed from a combination of the landmark data obtained from the GOES VISSR images and a Trilateration Range and Range Rate system installed as part of the overall GOES system.

A significant increase in the accuracy of the Earth locator grids has been achieved within the past two years. The use of orbit and attitude information obtained in part from GOES VISSR images reduced the error in the 24-hr predicted grids to an average of less than 40 km. Continued improvements during the past year have now reduced the average to less than 20 km. and we expect this to be less than 10 km. by the end of May 1977. The present area of greatest need is in quick reestablishment of acceptable navigational parameters following a satellite maneuver.

The introduction of a digital archive for certain portions of the GOES VISSR data in July 1976 represents a significant milestone in operational data processing. We currently archive five images per day on digital magnetic tape for each of the two GOES operational satellites. Except for limited ATS imagery, the NESS has not previously saved any of the unprocessed digital data from any of the satellites.

The GOES Data Processing is being used as a test bed to demonstrate the validity of the new procedures for operation, maintenance and management of the operational data processing facility. The concept of Life-Cycle Management for ADP Systems is being evaluated on short-term development tasks for GOES data processing. A major effort is now in process to implement a VISSR Data Base as an on-line information source in the NOAA Central Computer Facility. This Data Base is available to those with authorized access to the IBM S360/195 computers in the NOAA computer facility.

The operational computer programs have been inventoried for conversion and installation into the Centralized Automated Library Management System (CALMS). The exact amount of retrofitting and software documentation to be done to bring the old software to the current standards has not yet been decided.

For the interested reader, Johnson et al., 1976 have provided summary tables covering the main features of all satellites used operationally by NESS from TIROS-1 to the present.

TIROS-N Ground System - The TIROS-N satellite and its accompanying ground data handling system is the third generation operational polar satellite system. Mr. E.L. Heacock has described the sensors to be flown on TIROS-N in another paper in these Proceedings.

The Ground Data Handling System for TIROS-N will be very similar in conceptual design to that currently used in the ITOS system. A major change in the specifics is that it will be an all-digital system as opposed to the large analog portions in the ITOS system. Another major change is the installation of a mass storage device between the ingest/preprocessing computers and the large computers in the NOAA Central Computer Facility. The specific mass storage is the AMPEX TeraBit Memory (TBM) system. With this system we can achieve two major goals:

- Provide one day's worth of data ($2 * 10^{10}$ bits) in an on-line storage facility accessible to the NOAA Central Computer Facility.
- Archive all the digital data received from the TIROS-N type satellites.

To achieve these two goals we are installing data ingest computers with sufficient capacity to perform the preprocessing functions of calibration, Earth location and data quality control. The new techniques in software development and management are being used very extensively in the implementation of the ground data handling system. Using this technology we expect to achieve another major goal of operating and maintaining the data processing system for TIROS-N with no increase in manpower even though there are two operational spacecraft instead of one and the data flow rate is at least an order of magnitude larger.

FUTURE SATELLITE DATA PROCESSING - CIRCA 1980

The types of sensor data to be used in operational data processing can be specified in great detail through the time period of the early 1980's. The GOES satellite with a two channel scanning radiometer nearly identical with the present VISSR will provide the remotely sensed data from geostationary satellite altitudes. The sensor data from the polar-orbiting satellites in 1980 will come from the TIROS-N series of satellites.

The output products from the operational data processing in the early 1980's is not nearly as well known as the specifications for the input data. Indeed, the operational application of remotely sensed data is in a period of rapid change and our customers are becoming highly sophisticated in their uses of such data. The demand for image data is shifting from the photographic hard copy image to digital image data to enable the user to perform his own analysis and interpretation of such data.

Figure 7 shows the major features of the operational processing system that we believe is needed to obtain quantitative products from the geostationary (GOES) and polar (TIROS-N) satellite systems through the early 1980's.

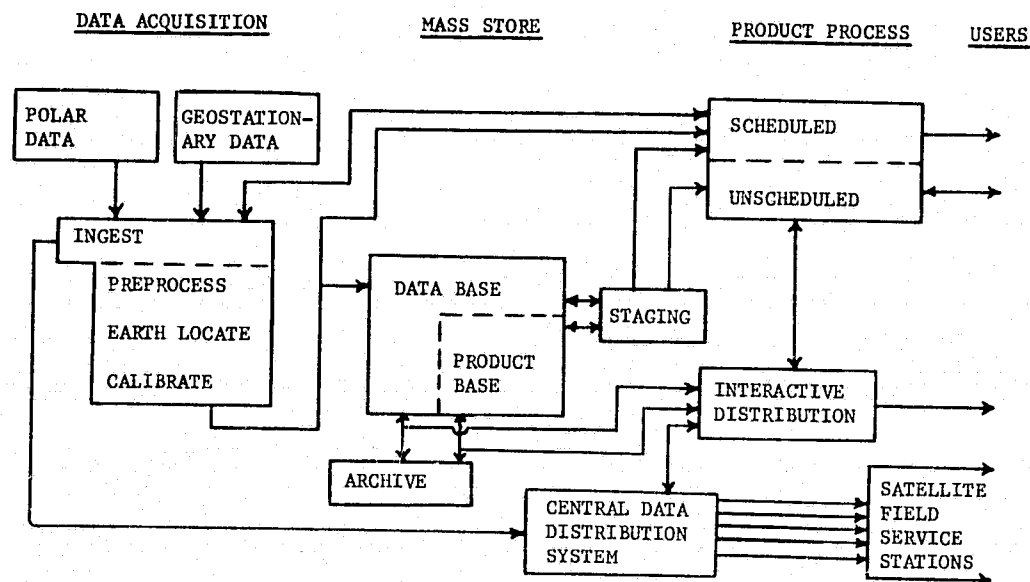


Figure 7. Future Satellite Digital Processing (Conceptual Design) Circa 1980

The beginning of the system, Data Acquisition, would be a dedicated system of mini-computers for the preprocessing functions of Earth location of the data, sensor calibration, formatting, and quality control of the ingest data. From ingest and preprocessing, the data pass to a large mass-storage system that would hold the data for transformation into products. Product processing will take place in large computers, like the IBM 360/195 of today, as well as in smaller, dedicated computers for specific functions. The products are returned to the mass-storage system for access by either archival or operational users. In this configuration the mass storage serves as both a data base and product storage facility.

The user interface in the 1980's should be an interactive system. The quality control of the final quantitative product line would be under the management of meteorologists who could interact with the product data base via interacting data display and data manipulation systems.

Another feature of this processing system is the ability to handle scheduled/unscheduled and archival production. Rather than being slaved to data ingest schedules (as with the present polar satellite system) that float from day to day, it is more efficient to process data on a regular clock schedule, which is geared to synoptic cycles and user needs. Unscheduled users could access the data base for immediate analysis of significant events such as thunderstorm or hurricane situations. A man-machine interactive system would serve as an efficient interface between the users and the product processing for both the scheduled and unscheduled processing.

Archival users are served in this system by being a part of it. By having an access to the mass-store system, both processed data and quantitative products are available for archive.

While the exact specifications for the output products in the 1980's are not known the application areas and the resultant characteristics of the satellite data requirements can be fairly well defined. For example, there are six general types of applications for the GOES VISSR data in digital form.

1. Precise geometric measurements on VISSR images for Satellite Winds and Landmark Navigation. The data base requirements for this application are short time period (< 12 hr) and a sector of 100 degrees longitude by 100 degrees latitude. Capability for precise picture registration and Earth location is also needed.
2. Quantitative processing of VISSR image data for output such as Sea Surface Temperature Gradients, Precipitation Measurements, Sunshine Duration at the Surface, Fire Danger Index, Soil Moisture, and Land Surface Temperature. This type of application puts a very stringent requirement on the data base in terms of sensor calibration and data quality standards. The geographic coverage is also a sector of 100 degrees longitude by 100 degrees latitude. The response time of the output is not very stringent (> 3 hrs). This type of application features the integration of image data at half-hourly or hourly intervals over a period of time. Specific examples of such integrations are:
 - (a) Integration of IR clear radiances over as much as six hours to average out the atmospheric moisture gradients to obtain accurate sea surface temperature gradients.
 - (b) Estimates of precipitation rates at half-hourly intervals integrated to obtain three or six hourly rainfall amounts at a geographic location.
 - (c) Estimates of cloud cover derived from half-hourly data integrated over daylight hours to yield sunshine duration at the surface as estimates of available solar insolation.

In this type of application there are tradeoffs possible between the computer capacity and the mass storage capacity to achieve a load leveling in the product processing.

3. Digital (quantitative) data support for users such as the Satellite Field Service Stations or the Weather Service Forecast offices. The data base requirements for this type of application are:
 - (a) Fast response time on an unscheduled basis.
 - (b) Very small sectors (on the order of 100 digital samples total).
 - (c) Sectors selected by users as needed.
 - (d) Short storage period (< 6 hrs).
4. Image analysis for Oceanographic and Hydrologic applications using a digital data base and a machine assisted manual processing mode. This type of application presents almost a pure tradeoff between the amount of on-line storage capacity and the number of persons needed to perform the machine assisted manual processing. On the one extreme, if we have the capacity for only one hour of on-line digital data storage then it will require 24 hrs. per day manual monitoring and processing or a

total of 10 people for two spacecraft. At the other extreme, if we have the capacity for five days of on-line digital data storage it may be possible to perform the manual monitoring and processing for two spacecraft by one person working a normal work week. The second extreme provides a savings of \$250K per year in manpower costs over the first extreme.

This type of application needs further definition to better determine the optimum configuration in terms of on-line storage capacity and the number of persons needed to perform the machine assisted manual processing.

5. Digital archive of VISSR data Earth located to serve secondary users. This application requires further definition in terms of the secondary users we will attempt to serve.
6. WEFAX (Weather Facsimile) broadcast of VISSR image sectors from random locations on the full disk image and immediately after the VISSR ingest of that full disk image is completed. This type of application provides image data to an international user community through a broadcast from GOES satellites.

We expect that our movement to the Data Base Management Concepts for handling remotely sensed data and products will be fully operational by 1980. In our application of these concepts we have developed a list of features that are essential for the design and implementation of a good data base system. These considerations include:

- Limited On-Line Space for "Unlimited" Applications - The commercial industry can now supply "Terabit" memory devices as an on-line storage device. Even this huge amount of storage represents less than 30 days worth of data from our 1980 operations of two GOES spacecraft and two TIROS-N type spacecraft.
- Automated with Manual Override - The data flow rate into the operational on-line data base is so large that it dictates a highly automated operation. Yet, the unpredictability of certain failures makes it necessary that quick reaction manual override be a significant part of this system.
- Quality Controlled and Secure - On-Line quality control with highly sophisticated diagnostics for trouble shooting is needed to minimize the time to detect problems and the time to repair such problems. A trade-off can be made between system redundancy and time to repair.
- Contain Supporting Information without altering data irreversibly - We need to perform certain preprocessing functions such as calibration, and Earth location before the data are stored on the data base. Certain functions can alter the data such that the originally measured value cannot be obtained after such a function is performed on the data. Mapping the data from its original perspective to a standard map projection is an example of such an irreversible process. We have chosen not to limit the type of processing which can be done on the data as a result of the preprocessing by not allowing any alteration of the data values which is not a reversible process.

- Archivable media - The amount of data received from the operational satellites makes it highly desirable that the storage media used for the on-line data base be capable of also being used as the storage media for the permanent data archive.
- Hierarchical Data Base and Response Times - Our requirements for data access times range over many orders of magnitude. We have found the cost/performance ratio is most advantageous if data less than 12 hrs. old is available in milliseconds, 12 to 24 hrs. old in seconds, and data more than 24 hrs. old should be accessible in minutes.

These access times permit us to build a data base consisting of permanently mounted disk packs for millisecond access, mounted tape reels on the AMPLEX terabit memory for access in seconds, and dismounted tape reels stored in a nearby vault for data access in minutes. Other features for the operational data base include:

- Directory for both accounting and status.
- Recovery procedures for minimizing loss of data.
- Standard access procedures to reduce software development costs, maximize number of users at minimum cost per user.

We believe that our description of operational data processing - CIRCA 1980 is realistic and considers significant factors such as level funding. We recognize that our projections are very conservative and do not take real advantage of developing hardware technology in data processing such as microcomputers. It is our belief that funding restrictions will lengthen the amount of time between demonstration of technical feasibility and realization of this capability in an on-going operational data processing facility. We prefer to include this type of discussion in a speculation on future operational data processing.

Beyond the beginning eighties, one may project current developments into likely demands for still more sophisticated products. The growing world food budget problem demands improvement in short term monitoring techniques as well as better crop yield projections. Expanding energy production and transformation operations, explorations, and experiments will require improved and diversified support. Increased emphasis on close management of sea life and the preservation and protection of estuaries and coastal wetlands will increase the need for precise monitoring and status determination. The growing computer power for numerical weather prediction at several world centers will help reduce past problems with mathematical truncation errors and so place even greater emphasis on the precision and volume of remotely sensed atmospheric measurements. Outputs from remote sensors to satisfy these more sophisticated demands must be based not only on precise calibration and earth location of raw data but must employ advanced models which will combine multi channel measurements (coincident in both space and time) so as to minimize the effects of variable contaminants or other unwanted "noise."

As these more precise, quantitative derivations evolve, concurrent facilities improvement efforts will likely keep pace so that transmission capacity and product handling capability will properly serve the user. The present Automation of Field Operations and Services (AFOS) effort within the National Weather Service will provide digital message transmission and local interactive computerized manipulating facilities for some 250 field users of weather information, and products from remote sensors will be included in the dissemination system. This project is described in a recent NOAA Program Development Plan (Anon. 1976). A somewhat related service is also under consideration within NESS whereby a much broader user base would have prompt access to quantitative operational products through a hierarchy of digital transmission and manipulative terminal alternatives. By the mid eighties, the

present satellite field services image data distribution system may also be transformed into a digital system and perhaps be considered a part of this hierarchy. Current efforts to expand WEFAX broadcasts beyond imagery into numeric messages and graphic analysis-prognosis material may also assist even the more basic receiving stations to become more quantitative in their usage.

The growing product demands and the improved dissemination and handling resources will also be accompanied by further growth and improvement in remote sensing programs. The maturing GOES mission will expand with the substitution of the VISSR Atmospheric Sounder (VAS) assuming the resources can be found to maintain operation. Denser and more frequent sets of indirect atmospheric soundings will result from the multi channel sounder, and the present two-channel imaging capability will continue.

By the mid eighties, the dual polar orbiter (TIROS-N series) will also be a mature operation, and advanced quantitative products from the all-digital 5-channel imaging scanner and multi-unit sounder will be meeting the global requirements as mentioned above. Experience with Seasat microwave sensors (Anon. 1977) and with Nimbus experimental sensors will have provided insight to supplement the continuing TIROS-N experience, and plans for a new polar orbiter system (TIROS-O) will have become firm. Since geostationary satellites are to be launched by Japan, the USSR, and the European Space Agency, we shall soon have the ability to essentially monitor the global weather pattern on a synoptic basis. Through international cooperation in extracting simultaneous wind estimates and other measureables, we may eventually alleviate the difficulty of blending asynoptic observations into analyses for numerical prediction. Such cooperation might therefore also influence the interplay of missions between polar orbiters and geostationary satellites and so influence the configuration of the fourth generation (presumably TIROS-O) operational polar satellite system. With continuing experience and an expanded sensor data input, and, with space shuttle operations lessening the cost of space operations, the opportunity for production progress seems assured.

Accepting all of the above concerning growing production demands and the supportive growth in remotely sensed information, the final consideration involves the question of data processing capabilities. Can production grow further in quantity, quality, and degree of sophistication with minimal expansion in the processing budget? The answer must consider both people and technology.

In budgeting for increased computer processing power, we are fortunate in that predictions of marked advancements with diminishing costs have erred on the conservative side. Inexpensive microprocessors are making all components into "smart devices," and large and medium scale systems are dropping in price as the same technology has its impact. Competition also seems to be growing in the development of economical array processors, pipeline systems, and related specialized image processing hardware. Whether eventual replacement of NOAA's 360/195 trio comes through larger central resources or expansion in distributed facilities, it appears that level funding for computers will continue to buy expanded support.

The management of human resources is a much more serious matter. Expanded operational production must not usurp developmental talent. This means that operational software must be devised so as to be essentially maintenance-free, and production control plus quality monitoring must be automated to the fullest possible extent. We believe the actions now under way -- to consider life cycle resource requirements, to devise a data base management system optimized for operational image data production, and to invoke realistic standards with a software library concept such as CALMS -- will go far to meet these demands.

The real economic payoff for an Earth application satellite operation such as the one described herein, involves maximum broadening of the base of users.

We believe progress is being made in that direction, and, with continuing emphasis on the critical deployment of human resources, we welcome the challenge of the eighties.

RELATED PAPERS IN THESE PROCEEDINGS

This technical paper on Operational Data Processing represents one of three invited review presentations on meteorological satellites. A paper on meteorological sensors by E.L. Heacock and a paper on operational data utilization by J.B. Jones were the other invited review presentations.

In addition, there were a number of Poster-Session presentations by persons from the National Environmental Satellite Service. The technical papers which were written as part of the Poster-Session presentations provide more detailed descriptions on a number of topics covered by our review paper on Operational Data Processing. We have included a list of the authors and titles of these papers here as a convenient listing for those wishing to obtain more detailed information.

- (P17) Brower, R.L. et al: Present and Future Operational NOAA Satellite Oceanographic Products: An Introduction.
- (P38) Miller, D.B. et al: Potential Applications of Digital, Visible and Infra-Red Data from Geostationary Environmental Satellites.
- (P59) Crowe, M.: Processing of Satellite Imagery at the National Environmental Satellite Service.
- (P79) McMillin, L.: Capabilities of Operational Infrared Sounding Systems from Satellite Altitude.
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OPERATIONAL UTILIZATION OF REMOTELY SENSED DATA

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ABSTRACT

This paper describes ways that data from environmental satellites and other remote sensing platforms are used in some of NOAA's operational service programs. Applications which have become routine, and those which are in advanced field test are included. Some applications yield a clear cut economic benefit. In other cases, benefits -- if any -- are obscure. In yet other cases, benefits in one sector may be offset by detriments in another. A few illustrative examples are given.

1. INTRODUCTION

In February 1971, NOAA published First Five Years of the Environmental Satellite Program -- An Assessment. During most of the period covered by this report, operational satellite data were limited to pictures taken once a day over the sunlit part of the world. Despite this rather severe limitation, beneficial use was made of the remotely sensed data from this first operational system. Toward the end of this first five year period, daytime cloud pictures taken every 30 minutes became available through an extensive operational use experiment with NASA's research and development geostationary Applications Technology Satellites, ATS-1 and -3. In the six years since this first assessment, we've been provided with more and better data from satellite and aircraft platforms, and we've learned how to use the data more effectively.

2. 1971-1977 UPDATE

This section heading is a slight misnomer because some of the specific examples of applications are taken from the first five years experience. Most however, are examples of new things or old things done better.

2.1 HURRICANES

The use of satellite pictures to find and track hurricanes and lesser tropical storms dates back to the early days of the TIROS program. Since the inauguration of the operational weather satellite service in 1966, probably no tropical storm has gone undetected, and almost invariably the storms are seen first by satellite. Not only has the U.S. integrated the satellite observations into its hurricane warning service, it shares with the rest of the world the tropical storm surveillance capability of the satellite.

In 1974, the Geostationary Operation Environmental Satellite (GOES) system was launched, giving us near continuous around the clock surveillance of the tropical Atlantic and eastern Pacific. Satellite navigation improved, and along with it the ability to locate cloud features more accurately. And a Satellite Field Services Station was collocated in Miami with the National Hurricane Center, in San Francisco with the eastern Pacific Hurricane Center and in Honolulu with the Central Pacific Hurricane Center. Early detection and nearly continuous surveillance have helped us improve short term warning service to shipping and coastal communities. Before satellites it wasn't uncommon to learn of a developing storm when a ship ran into it and told us about it. Satellite surveillance now helps us tell the mariner where the storms are, leaving it to his discretion then whether to proceed or alter course. These improvements provide potential economic and social benefits, but the public has a vital role to play in realizing the potential. More reliable and timely warnings return a benefit only if the public develops and follows a rational plan of action.

The early and reliable detection and tracking of hurricanes by satellites has yielded some direct benefits in the form of cost avoidance. By the early 1970s, tropical storm reconnaissance aircraft flights were reduced by some one million to two million dollars annually. Satellites

handled the surveillance chores and aircraft were directed to the storm to take observations. Also, if one can avoid preparing for a hurricane that doesn't develop, savings can be realized. An example of saving hurricane preparedness costs reported in First Five Years... is paraphrased here.

When a storm is forecast to become a hurricane and is named, communities which lie in the forecast path must take extensive precautions. Preparation costs for a city the size of Miami have been calculated at \$2,000,000 for a single storm. The cost of even one false alarm can be exceedingly high. In August 1970, satellites and aircraft observed a tropical disturbance moving across the Atlantic. Aircraft measured winds of 70 miles per hour in the storm. Normally, when winds this strong are found, the disturbance is named, warnings are issued, and coastal communities begin preparing for a blow. In this case, satellite pictures showed this wasn't a rotating storm and wasn't an immediate threat to intensify. Forecasters followed the storm a few more hours, decided it wouldn't become a hurricane, and therefore did not issue an unnecessary warning. The storm weakened and moved inland without reaching hurricane force.

2.2 SEVERE LOCAL STORMS AND TORNADOS

The ATS-1 and ATS-3 satellites took pictures at 30 minute intervals and gave us an opportunity to observe development, growth, and decay of convective cloud systems that contained local severe storms and tornados. With this capability, the satellite cloud pictures began contributing to the severe weather warning services in the U.S. The GOES system, launched in 1974, included a nighttime observing capability, a real time picture distribution system, and special data processing and display features including picture enhancement and routine time-lapse display that made it possible for meteorologists to study the cloud motions observed by the satellite. The GOES pictures provide important information for the severe storms and tornado warning service. In the larger scale, the cloud motion observations help detect and follow weather features often associated with severe weather development -- fronts, the subtropical jet stream and areas of convergence in low level cloud fields. These are helpful in diagnosing the potential for severe weather development. GOES also sees the onset of convective activity before it has developed sufficiently to be detected by radar.

Meteorologists observed that squallines often developed from the small cloud lines the satellite detected at the onset of convection, when these small cumulus lines lay within areas where general conditions were favorable for heavy thunderstorm development. These "first detectable" convective cloud lines are now used routinely to locate and orient the areas or "boxes" within which severe weather watches are issued to the public. The following is an early example, documented in the spring of 1974 while we were still learning from ATS-3 pictures while awaiting the launch of the first satellite of the GOES system.

"On Friday, April 26, the ATS-3 series of pictures was extremely helpful in the timing, location and shape of severe thunderstorm watch #176.

Analyses of conventional data for 12Z and progs for 00Z/27... showed good potential for convective activity over much of South Dakota and Nebraska... however, the area was relatively cloud free and the radar summary chart as late as 2035Z showed nothing in that area.

The ATS-3 picture showed the early stages of a developing N-S line of organized clouds... which was the tip-off that convective activity would develop." A line of thunderstorms was seen on the radar chart about an hour later, the severe thunderstorm watch was issued at 2230Z with the western edge of the "box" oriented along the line of clouds seen in the ATS-3 picture. By 0030Z thunderstorm tops to 54,000 feet and golf ball size hail were reported in central Nebraska. (Memo for Record, Deputy Director, National Severe Storm Forecast Center, 5/1/74).

Forecasters have learned also to look for indications of positive vorticity advection approaching an area where all the conditions for severe weather exist except the impulse to trigger the activity. The following paraphrases a report of an event where the satellite data discovered the "trigger".

During the morning of March 20, 1974, meteorologists at the National Severe Storm Forecast Center had determined that Louisiana and east Texas had most of the conditions necessary for severe weather outbreak. Shortly after noon, a satellite meteorologist with the Kansas City Satellite Field Services Station detected a short wave trough moving out of northern Mexico into southwest Texas. This feature was tracked for the rest of the daylight hours, establishing its direction and rate of movement. Forecasters calculated when this upper level trough would arrive over east Texas and forecast the severe weather outbreak to begin at that time. Numerous severe thunderstorms and several tornados were reported over east Texas and the state of Louisiana. Director, NSSFC stated that the satellite data had played an important role in issuing a timely and accurate severe weather watch. (Memo from the Manager, Satellite Field Services Station, Kansas City, 3/26/74).

As illustrated by these examples, satellite observations help us improve the timeliness and reliability of our severe weather advisory service. This provides the potential social benefit of fewer injuries and deaths from severe thunderstorms and tornados. Again, a well thought out and well executed emergency action plan by the community is vitally important if this potential benefit is to be realized.

2.3 FORECAST GUIDANCE

Forecast guidance products for periods from 12 hours out to several days are prepared at the National Meteorological Center (NMC) in Washington, D.C. These products provide the basic forecast charts used by the Weather Service Forecast Offices and the Weather Service Offices. Much of the data used in the production of the guidance materials comes from the satellite system. Cloud pictures are used to detect and position weather systems over ocean areas of the world and are used directly in preparing weather depiction charts for guidance to the aviation weather service program. Winds derived from the GOES cloud motion observations add useful detail to the machine produced analyses of upper level wind fields and provide the major source of data for the wind field analyses prepared for the tropical regions. Beginning in 1972, atmospheric temperature soundings from the polar orbiting NOAA satellite system have been added to the data base used in the numerical weather forecast models at NMC. We had expected by now that these new data would lead to a measurable improvement in numerical weather forecasts. Carefully controlled tests have been conducted to evaluate the impact of the satellite soundings on the analyses and forecasts. Results indicate that soundings from this generation of satellite instruments used in today's operational forecast models have had no significant affect on the accuracy of numerical analyses and forecasts. Work is continuing on the next generation models and atmospheric sounders in an effort to improve this situation.

2.4 PUBLIC WEATHER

Pictures from GOES are now received routinely, with only a few minutes delay, at all Weather Service Forecast Offices (WSFOs). These cloud observations together with satellite interpretation messages, produced regularly by the NESS Satellite Field Service Stations, are an important source of information for the short term weather forecasts issued to the public. Forecasters use the satellite information to monitor and amend the forecasts issued in the first 12 hours of the guidance forecast material issued from the NMC. Forecast offices report they're able, in many cases, to improve the accuracy of the short term forecasts for the beginning and ending of precipitation, local changes in cloud cover, the onset of heavy thunderstorm activity with its associated hazards, and other events of interest to the general public. A few cases of how the satellite pictures helped produce a better forecast are described below.

On November 24, 1975, WSFO Portland, Maine modified forecast guidance on the strength of the satellite observations and made important changes in the forecast issued to the public. Based on guidance from the National Meteorological Center, the early morning forecast issued by Portland at 0930Z called for "...rain beginning tonight along coastal sections of Maine and New Hampshire...light snow likely tonight in the mountains...and a chance of snow in the far northern reaches of Maine late at night." From the GOES pictures received during the morning of November 24, it was apparent the storm center was moving on a trajectory that would carry it further off-shore than was forecast in the short term guidance material. On the basis of these indications, an amended forecast was issued calling for "...snow tonight, tapering off by midnight in southwestern Maine and by daybreak in eastern Maine." Accumulations of two to four inches were forecast for coastal areas and gale warnings

were issued for the area. This amended forecast verified well -- all precipitation fell as snow with heaviest amounts (four to five inches) along the coastal areas. The difference between "rain, occasionally mixed with snow" and snow accumulating up to five inches is dramatic to the traveller and the commuter.

On December 22, 1975, a storm had passed New York City and was moving northeastward away from the area. At 11:00 a.m. the forecast called for clearing skies and no further precipitation. By early afternoon, the satellite pictures showed another small storm center approaching the city and the forecast was amended calling for an additional snowfall of "...up to three inches" for New York City and suburbs. Two to three inches of snow fell -- residents of the area had been forewarned.

During April 2 and 3, 1975, WSFO Detroit used the GOES picture information to correctly advise communities in Michigan of moderate to heavy snowfall. Time of onset was forecast accurately and the ending of the snow fall was forecast accurately some 10 to 12 hours in advance.

On a day in April 1975, forecasters at Minneapolis, Milwaukee, and Chicago correctly identified thunderstorms imbedded in a fairly extensive cloud system observed by GOES. Public and aviation forecasts were amended to include mention of the thunderstorms, and were issued before these storms had been detected in the more conventional surface and radar observing networks.

On October 6, 1975, a moist southerly flow had produced a blanket of fog and stratus over much of the lower Mississippi valley and extreme eastern Texas. According to surface reports, this area was covered uniformly, but pictures from GOES indicated one or two thin spots in the fog blanket -- these were located in spaces between surface reporting stations. Forecasters had learned that fog would begin to burn off first where it was thinnest and, in this case, were able to forecast and monitor the gradual dissipation of the fog over an ever widening circle, as the clearing approached several cities in the area. The satellite pictures provided the information needed to make an accurate forecast for the time of fog dissipation at several cities in northern Louisiana. Knowledge of the extent of low cloud and fog, and how rapidly the cover is changing, is important to travellers weather advisory service and to general aviation where many pilots must maintain visual flight rules.

Satellite pictures received at Seattle during the night and early morning of May 28-29, 1976, enabled the forecaster to make an important amendment to an earlier forecast and issue accurate gale warnings for the Straits of Juan de Fuca and inland waters of western Washington for the Memorial Day weekend. Many boating activities were scheduled, including an organized sailing race in the Straits.

During the period April 2-4, 1974, the weather maps prepared from conventional observations indicated a general flow aloft from south to north over the eastern Pacific. This usually results in clear skies and warm temperatures over the intermountain regions of the western U.S. Satellite cloud pictures showed the flow over the eastern Pacific was more westerly. Cloudy skies were forecast for the western U.S. along with lower temperatures. Without the satellite observation, we'd have busted this one by calling for clear skies instead of cloudy and surface temperatures 15 to 20 deg. too warm.

Forecasts released early on November 10, 1976, by the Albany WSFO called for mostly cloudy with occasional light snow, but little or no accumulations. Within the next two hours the series of GOES pictures showed an intensifying and rapidly moving weather system to the west of Albany forecast area. Based on this information, the public weather forecast was revised to call for snow accumulating one to three inches, before ending in the afternoon. The timing of the revised forecast was good and the Albany forecast area had two to three inches of new snow on the ground when the storm cleared the State by mid-afternoon.

More recently, the GOES pictures helped WSFO Columbia, South Carolina forecast accurately a major dust "episode" over the state, perhaps the first since the 1930s. Late in February 1977 strong winds moved across the western and central plains, picking up

vast clouds of dust and transporting them eastward. These dust clouds were easily identified and followed in the GOES pictures -- both visible and infrared. To paraphrase a brief technical report on the event, GOES provided accurate information on the leading edge, areal extent, relative strength, and forward speed of the dust cloud. This enabled the WSFO staff to issue accurate forecasts on the beginning and duration of the dust storm. The public was keenly interested in the dust, which reduced visibility dramatically. The satellite pictures were used to provide current detailed briefing information to press, radio, and television during the height of the dust storm. GOES photos also made it possible to give accurate forecasts of improvements from the dust storm. (Eastern Region Technical Attachment, No. 77-6, 3/14/77).

And then there are the relatively few times when a forecaster is misled by the short term trends shown in the GOES pictures received every 30 minutes. On December 29, 1976, WSFO Boston had tracked the western edge of a cloud system as it approached the Boston area. Snow was falling east of this cloud edge and clearing was taking place to the west. Boston measured the rate at which the cloud edge was moving eastward and by extrapolation forecast a time for passage at Boston. Clearing approached Boston, then stopped -- snow fall continued for several hours more and six additional inches of snow accumulated.

Over the past three years, as forecasters have learned to interpret the GOES cloud observations, the satellite has become an increasingly important tool in our public forecast service. The ability to observe short term local trends has helped us improve the accuracy of public forecasts in the first 12 hours of the forecast period. We believe the public accrues a social benefit from the improvements in short term weather forecasts. Economic benefits are difficult to assess, although the more accurate forecasts of snowfall should help in the more efficient management of snow removal resources.

2.5 HYDROLOGY

Data from remote sensing systems also play a role in our river forecast and flood warning services. Heavy rain storms moving inland from ocean areas and from decaying tropical storms can cause dangerous flooding. Slow moving systems of heavy thunderstorm activity can cause serious flash flooding -- witness the Big Thompson Canyon disaster of 1976. Experience in interpreting satellite pictures and the more recent around the clock surveillance by GOES have helped identify and track storms moving in from the data sparse ocean areas and the decaying tropical storms, reducing the number of times we and our customers have been surprised by flood producing rains. In these cases, timely warnings were issued and benefits of both a social and economic nature were realized.

During the first 10 days of January 1974, the movement of storms into the Pacific northwest had been blocked. Toward the end of this period, forecasters in our Western Region saw trends in the satellite cloud observations that indicated a breaking down of the block that would result in a period of heavy rain over the area. Forecasts were issued for rain beginning January 11 with the indication that heavy rains could be expected for several consecutive days. In addition to the public, these forecasts were issued to water resources management groups responsible for controlling water levels in reservoirs for conservation and flood control. The forecasts were accurate and timely; heavy rains fell and widespread flooding occurred in western Oregon -- eleven lives were lost and property damage reached an estimated damage of \$65,000,000. Without the timely and accurate warnings, the casualty and damage figures would have been considerably higher. Our Western Region forecasters gave major credit to the satellite observations.

During the early morning hours of September 26, 1975, the Susquehanna River basin was getting heavy rain from the nearly stationary remnants of tropical storm ELOISE which had moved northward from the Gulf coast. Eastern Pennsylvania and southern New England were being threatened with serious flooding. Forecasters were reassessing the situation almost hourly to warn where needed and avoid unneeded warnings where possible. Movement of the rain producing ELOISE was the major factor in calling the shots. Radar coverage was just about adequate because of the relatively large distance

of the storm from the nearest radars. Analysis of pictures from the GOES system indicated the rain system was moving eastward at about 8 to 10 miles per hour with the western edge of the activity, where rainfall ended, clearly defined. Using these pictures at 30 minute intervals, meteorologists of the Eastern Region kept the storm system under constant surveillance throughout the day. This enabled them to forecast correctly the time when rainfall would end over parts of the basin, and provide timely and accurate river stage forecasts to communities in the basin. The Director of the Eastern Region concluded his report of this event with the following: "In short, I found the SMS-1 information (GOES system pictures) invaluable during the siege with "ELOISE" and particularly so during the critical stage in the Susquehanna Basin."

In each of the examples above, satellite observations made the principal contribution to timely and reliable advisories from which the involved communities realized both social and economic benefits.

Satellite pictures also help monitor snow cover in major U.S. river basins and this information is used to help assess the potential runoff. The satellite, however, doesn't provide a measure of the water equivalent of the snow pack, another piece of information vital to the runoff assessment. NWS, in cooperation with other agencies, tested aerial monitoring of gamma radiation as a way to get timely and accurate information of this quantity. Results from the 1974-75 tests showed that gamma measurements are comparable to measurements from extensive ground sampling and demonstrated the operational capability of the system. We don't yet have an operational system, but because of heavy snow during the winter of 1976-1977, arrangements were made for gamma radiation flights over the Lake Ontario and Lake Erie Basins near Buffalo in March 1977.

Most recently, scientists of NOAA's Environmental Research Laboratories and NESS are working to develop techniques for estimating rainfall rates from enhanced infrared pictures of heavy convective cloud systems. Systems such as this can produce extremely heavy rains and can produce flash floods of the magnitude that devastated the Big Thompson Canyon in 1976. First results of this work indicate some skill in estimating rainfall rates and total rainfall.

2.6 SPECIALIZED SERVICES

These services include support to space programs, maritime operations, fruit and truck farming, search and rescue operations, and to wildlife management.

2.6.1 SPACE PROGRAM

In preparing for the Mariner flights to Jupiter and Saturn, the Jet Propulsion Laboratory is developing a computer model to predict in near real time the degradation of X-band communications under various weather conditions. Forecasts of several factors, including moisture, cloud types and amounts from the surface to about 6km are produced each day to support the development of the model. GOES pictures provide much of the information about cloud type and distribution.

At the Johnson Space Center, meteorologists of the NWS Spaceflight Meteorology Group forecast weather and cloud conditions to support the Airborne Instrumentation Research Program, part of NASA's Earth Resources Program. Satellite observations are an important source of information about cloud cover for these forecasts.

NASA Goddard Spaceflight Center operates the LANDSAT program, taking pictures everyday on a global basis. To conserve power and make effective use of limited on-board tape recorder storage, the satellites in the system are programmed to take pictures only over those parts of the world where there's a good chance to see the ground. Global cloud forecasts, provided by the Spaceflight Meteorology Group, depend heavily on the global cloud cover observations from the polar orbiting NOAA satellites.

2.6.2 MARINE OPERATIONS

Temperature gradients associated with upwelling and major ocean currents can be seen on clear to partly cloudy days by the infrared scanners in the NOAA and GOES satellites. These features are of practical interest to shipping and fishing operations.

In 1975, the EXXON Company conducted a test to determine if improved day-to-day knowledge of the Gulf Stream location could improve navigation enough to realize significant fuel savings. NOAA produced analyses of the Gulf Stream location twice a week from satellite infrared observations and sent them to EXXON. Eleven EXXON tankers participated in the controlled test. Five were instructed to follow standard navigation practices for using or avoiding the Gulf Stream and the other six, to navigate according to the up-to-date satellite information on Gulf Stream location. A summary at the end of the season showed an average round trip savings of about 3% for those vessels using the satellite derived Gulf Stream analysis. EXXON projected a potential fuel savings of some 31,500 barrels of fuel oil with a dollar value of \$360,000 (assumed a total of 15 tankers navigating by the satellite Gulf Stream analysis). Applied to all coastal shipping, savings in operating and fuel costs could be really significant. (Note: a more complete account of the EXXON test is found in the September 1976 issue of Gulf Stream Magazine.)

More recently, NOAA has started preparing an analysis of the Gulf of Mexico Loop Current from satellite infrared observations for test use by shipping and fishing operators. The Loop Current analysis was distributed on an experimental basis for several weeks beginning in December 1976 to test user reaction. Response was positive. Fishermen looking for the thermal boundary of the current could sail directly to it -- some, noting that it lay beyond the range of their boats, saved fuel and expense by staying in port. The earlier practice was to start out into the Gulf toward the usual location of the current and continue until the current was found. If the vessel reached the limit of its cruising range without finding the current, it turned around and came home. Cargo vessels following the analyses were able to use or avoid the current and register saving in time and fuel. In January 1977 potential marine users were surveyed -- did they think the service useful and would they like to receive the analysis routinely. Ship masters and shipping superintendents representing about 200 ships responded positively -- among them several large oil and ocean transport companies. In his response the executive vice president for one company stated, "We are presently using the single side-band broadcast for the West Wall of the (Gulf) Stream in the southeastern Atlantic region which has been of great value."

Off the Pacific coast, commercial and sports fishermen look for thermal fronts associated with upwelling and ocean currents to locate varieties of fish. In 1975, NOAA began a cooperative program to produce up-to-date, detailed analyses of these thermal features from satellite infrared measurements and distribute them to fishermen for a test. During this test, some 200 fishermen used the service. An average saving of several hundred dollars in fuel was estimated for each of the participating boats. In 1976, the distribution system was expanded to reach an estimated several thousand vessels. In 1977, the analysis will be extended southward from San Diego to the Baja region. One albacore fisherman had this to say about this special service: "In spite of the bad weather last season, everytime I used one of those charts, the fish were right where they were supposed to be. You can't ask for anything better than that." (A more complete account is found in NOAA, Vol 6, No. 1, January 1976).

With the advent of the high (1km) resolution images and twice daily coverage from NOAA satellites and the Defense Meteorological Satellite Program (DMSP), the satellite has grown in importance as an ice surveillance vehicle. An early benefit in terms of cost avoidance was realized when routine ice surveillance air patrols over much of the Arctic were eliminated or reduced substantially. Side looking airborne radar has proved useful for getting needed detail about ice distribution for shipping on the Great Lakes. Here's another case where remote sensing from satellites and aircraft have found practical application -- improved ice surveillance and forecasting. But this appears to be at least one case where not everyone is happy about what we're doing with the technology. This ice surveillance and forecasting service is generally well received by shipping companies carrying equipment and supplies to the North Slope and those operating on the Great Lakes. Shippers with cargo enroute benefit also -- better ice surveillance and forecasting increases safety, reliability and, in the case of the Great Lakes, has been a factor in extending the shipping season. However, some groups and communities along the Lakes have viewed this as a detriment. It's disrupted the winter time life style of some communities and some groups claim the practice threatens the ecology of the area.

2.6.3 SEARCH AND RESCUE

When planning a search and rescue mission, the U.S. Coast Guard often contacts the NESS Washington Satellite Field Services Station for the most recent information on sea surface temperature and the location of ocean currents, including small scale eddies. The NESS unit

derives this information from satellite IR measurements and provides the service on an on-call basis in addition to distributing similar products on a regular schedule. In general, the satellite surveillance is more timely than sending an aircraft and it avoids the cost of the aircraft reconnaissance flight. In 1975, NESS estimated savings of time and fuel on the order of \$30k. There's no way of estimating the savings of life and property. Presumably some rescues were made more quickly through information derived from the satellite data and this must be counted as a social benefit.

The Civil Air Patrol (CAP) in California with the NESS Satellite Field Services Station and the NWS Forecast Office in Redwood City has developed procedures for using satellite cloud observations in the CAP search and rescue operations. When an aircraft is reported overdue and presumed down, meteorologists and the search and rescue planners examine satellite pictures coinciding with the time of the flight plan, looking for signs of weather conditions along the route that could be hazardous for the particular aircraft and pilot. This preplanning with the satellite pictures has helped narrow the search area and reduced search time substantially. This increases the chances of finding survivors -- an unquestionable social benefit. Search time and fuel are saved also.

2.6.4 WILDLIFE MANAGEMENT

Wildlife managers who must establish hunting regulations for Canada geese are now using satellite pictures from NOAA to help them assess the probable bird population at the end of each nesting season. These figures are used to set bag limits for the coming hunting season. One factor important to the reproductive success of the Canada goose is the timely disappearance of snow and ice in the nesting regions and the availability of melt water to allow for production and rearing of young birds. If the season is late or weather adverse, population growth is inhibited. The NOAA polar orbiting satellites provide pictures of snow and ice conditions in the traditional arctic nesting areas and help the waterfowl manager assess conditions faced by the nesting geese in areas too remote for on-site inspection. The pictures help identify probable times and areas of extreme -- catastrophic or outstanding -- goose production permitting the manager to set appropriate hunting limits.

SUMMARY

NOAA uses remotely sensed data -- mostly from the operational environmental satellite system -- in weather forecast and warning services plus specialized marine, agriculture, and search and rescue support. We believe these data have helped improve the quality of many of these environmental services. It's hard to define quantitatively the value of a public weather forecast, but we believe social benefits do accrue. In some of the more specialized services, such as support to ship routing, economic benefits are more easily estimated and appear to be substantial.

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REBIRTH OF REMOTE SENSING -
DO WE KNOW ENOUGH FOR OUR OWN GOOD?*

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It is a pleasure to be here in Ann Arbor, Michigan, for the Eleventh Symposium on Remote Sensing of Environment, and I appreciate the opportunity to address a few words that may express a new appreciation of the contributions which we expect from your field to major and immediate problems.

I am aware that the history of this symposium--over 15 years and 1,000 papers--spans the development of the "art" and provides the basic reference through the invaluable resulting Proceedings. I am pleased that the Department I represent has been represented so continuously and substantially in this history. I am further impressed by the substantial international representation, and by plans to move meetings of alternate sessions to foreign centers to emphasize the "International" scope of your investigations.

On this occasion, I wish to underline the last word of this Symposium on Remote Sensing of Environment. Environment, taken broadly to refer to concern for our resources, the quality of the air and water, the wise production of energy. The theme of my remarks concerns the "payoff" stemming from the intensive scientific investigations of your group and the substantial R and D investments of the government, in particular for global earth observation satellite systems.

I myself am a natural scientist of the old school. Like Aristotle I started my career as a student and disciple of Plato. For many years I considered mathematics as an abstraction from natural reality. More recently responsibilities of my recent jobs have driven home, even if Aristotle and Plato did not. I have come to recognize the impact of reality.

The present way of comprehending the natural world is a very recent development, and I must confess to having to labor mightily to simply keep abreast of what you scientists are up to these days.

Before I discuss what avenues this administration is to explore in your field, let me remind myself and you in this audience of one very important historical fact. It should humble us all for a moment, at least.

In this Nation we rely heavily on science and technology. We should, all of us, I believe, remember that it was possible for great civilizations of the past to achieve highly developed technologies and religious and legal systems in the complete absence of a conception of science as it is now understood. Such were the civilizations of ancient Egypt, Mesopotamia, India, and

*An address by Mr. Herbst to the 11th International Symposium on Remote Sensing of Environment, Ann Arbor, Michigan, April 26, 1977.

the Western Hemisphere. Even the Hebrews, people whose religion forms a large part of the basis of European civilization, were indifferent to science. Although the Greeks created a system of thought that was similar to the scientific, in succeeding centuries there was little progress beyond their achievements and little comprehension of it. In the modern world, science has enjoyed continuous progress for only some 500 years, even though most of that period it was of minor interest among a cultural elite. The lives of ordinary people were affected only in the most indirect ways by the thoughts of scientists and the application of their results. The great power of science and its pervasive influence on all aspects of life are, thus, very recent developments. Let us not forget this.

Instead, let us remember that today there is a widespread reaction against any tendency to treat social or practical decisions as technical matters which can be left to the judgment of scientific or technological experts.

The general methods of technology may, indeed, represent practical applications of the theoretical understanding arrived at by science, but, all individual decisions about putting those general techniques to use, for, say, building an airport or a power plant, must be made not by appealing to any general formula or rule of thumb, but by balancing a whole range of diverse considerations--economic and aesthetic, environmental and human, as well as merely technical.

The title of my address is Rebirth of Remote Sensing: Do We Know Enough for Our Own Good?

I think we do. I believe President Carter thinks we do, and he is a man of scientific training and experience. He is also a man of humanistic experience in the realm of politics.

I have come to outline in broad form a view presently held within this administration of the general direction in which we intend to make advances that will benefit not simply science, but, more importantly, the citizens of this Nation, and indeed citizens around the world.

I did not come here with specific details of President Carter's plans for the use of remote sensing. I can simply state that he is well briefed on all aspects of current programs and experiments in this field.

He said while he was the Governor of Georgia, and I quote: "I believe that application of space technology to solving global as well as state and national problems is one way by which American know-how can make unique and lasting contributions to the welfare of mankind."

I am aware personally of recommendations made to the Secretary of the Interior and to the President. They should be of particular interest to you in this audience.

First I should like to address the problems of applying the data collected by the Landsat family, in conjunction with aircraft and ground observations, to our urgent problems.

As you all know, Landsat-1 and -2 were launched in July 1972 and January 1975, respectively. These very successful earth observation satellites continue to provide large amounts of high-quality data throughout the world that have made it possible to:

1. Demonstrate the applications of multispectral, multitemporal, space-acquired data to regional, national, and global resource assessment and environmental monitoring;

2. Develop rapid analysis techniques, including machine-aided analysis, to extract needed resource and environmental information from the satellite data in a format that can be incorporated directly into computerized information systems;
3. Make comparisons of resource and environmental problems on the basis of uniform worldwide data;
4. Show that international sensitivities concerning data acquired over foreign territories are not serious since most nations recognize that the benefits outweigh the risks;
5. Reaffirm the U.S. policy for open distribution of global data acquired from the Landsat satellites.

Let me now explore some obstacles or deficiencies in the on-going satellites that impede operational use of the data.

For some operational applications, Landsat data will be required by the user within 24-72 hours of acquisition by the satellite. The current system does not permit such rapid utilization. I understand that Canadian and other foreign reception stations have already implemented methods to provide for more rapid data availability.

Following the launch of Landsat-C in 1977, an entirely new satellite, Landsat-D, is being planned by NASA for launch in 1981. At this time, there is no planned backup for Landsat-C, and the time between planned launches does not provide assurance of continuity in the event of failure.

In addition, Landsat-D will have a new orbit. Thus, the spectral and spatial characteristics of Landsat-D sensors are different from the earlier satellites. While such factors are to be expected in an experimental program, they deter operational planning and data use. To ensure that the benefits of this technology can be realized, it appears that what may be needed is an operational program, which is operated in parallel with the experimental and technology development programs.

The experimental program began through the initiative of Secretary of the Interior Udall during the mid-1960's. Subsequently, the Congress provided strong support to both NASA and Interior to proceed with the experimental program and has encouraged implementation of operational phases of the program.

However, the enabling legislation of NASA does not provide for operational activities. Thus far agreement has not been reached for the necessary institutional arrangements. We recognize the need for solutions to the institutional arrangements which could lead to an effective program.

A possible clue to the shape of future management organization is offered by a bill, S. 657, introduced on February 7, 1977. This bill would assign operational responsibility for the space segment of the program to NASA. Responsibility for the ground segment would be assigned to the Secretary of the Interior, and responsibility for coordination and policy would be assigned to the Director of the Office of Science and Technology Policy.

I am aware that remote sensing devices encompass a wide variety of devices and applications. I have chosen for this talk to look with particular attention to the satellite sensor, readout system of great importance to my Department, the Landsat satellite system. Now, as to current applications, this system has been providing data to Interior bureaus for research and development since its beginning in 1972. I will cite bureaus which have demonstrated that the data can be used in their normal operations.

The Geological Survey, for example, routinely uses Landsat data in a multitude of research and investigative projects. These cover problems such as mineral resource investigation in Alaska, changing environmental conditions in wetlands, land use mapping, preparation of environmental impact statements, water resources exploration, and mapping of natural hazards.

The Bureau of Land Management has conducted sufficient research in Landsat applications for their missions to proceed with major investments in programs and systems to use Landsat to support their operational activities.

The Bureau of Reclamation is similarly investing in a digital Landsat analysis system to use for mapping and monitoring of agricultural areas for irrigation water management.

The Bureau of Mines has had outstanding success in mapping clay mines in South Carolina with digital Landsat data, which is expected to lead to a capability for monitoring land use changes caused by mining and reclamation of mined lands.

The U.S. Fish and Wildlife Service is quite active in using Landsat digital data for mapping and monitoring effects of mining on wildlife habitat in the western energy lands. Landsat data are also being investigated for basic inventories such as the national wetlands program and is used for monitoring freeze/thaw conditions in the Arctic breeding grounds of migratory waterfowl in order to predict waterfowl populations.

Recent Federal and State legislation drives the need for better collection and handling of data; for example, the Coastal Zone Management Act, Environmental Protection Agency Section 208 - Areawide Waste Treatment Program, Oregon Land Conservation and Development Act, New York State Mined Land Reclamation Act, etc., require timely information over large areas.

Frequently, basic data are not available or are outdated, and new data are costly to acquire. Landsat data offer an attractive alternative since data are collected repetitively and cloud-free data are available for the entire United States at a modest cost to the user.

Another hallmark of this Administration is close cooperation with State and local organizations. Recently, a survey was conducted in which regional and State agencies were asked to comment on the usefulness of the Landsat program to help meet their present and anticipated environmental information requirements. Responses were received from two National State interest groups, five multistate organizations, 23 individual States, and 9 substate organizations. The replies, now being analyzed, are positive.

Expressions of support were also received from the National Governors Conference, National Conference of State Legislatures, Southern Governors Conference, and 18 States. Further, additional specific examples of the utility of Landsat data were provided in responses from 12 State governments.

Now, to turn to international applications; within a year of its launch in 1972 the enormous capability of the Landsat system for providing a universal global base of data had been demonstrated. This could help overcome a dearth of environmental information over large land areas and some shallow water oceanic areas. It could standardize and improve natural resource data systems everywhere, as well as provide data for research applied to the Earth sciences and related environmental fields. A growing use of the Landsat images is being made on cooperative overseas assignments, for example the Geological Survey and National Park Service teams in Saudi Arabia, and Geological Survey minerals exploration programs in Thailand.

Other countries are investing major resources of their own in anticipation of an operational system. Canada, Brazil, and Italy have constructed Landsat data reception stations. A temporary station is operating in Pakistan. Iran will complete its station in 1977. Other nations, including Zaire and Argentina, are developing stations to improve coverage of their regions. Algeria, the Economic Commission for Africa, and the U.N. Food and Agricultural Organization plan acquisition of comparable facilities based largely upon proposed use of Landsat data.

The Interior Department, with other Departments, is sharing its expertise in Earth resources and its experience and capability for applying aerospace technology to the solution of development and management problems. This Department can continue to be available to serve, in a sense, as a technical arm of the U.S. Government in assisting international resource activities in the Earth and environmental sciences that employ remote sensing.

I would like to cite one example, which relates to my area of responsibility, which suggests the framework within which future cooperation can function. This is the Convention on Nature Protection and Wildlife Preservation--in the Western Hemisphere which has been ratified by 19 countries. This convention calls on the countries of the Hemisphere to establish natural parks and reserves to conserve their wild flora and fauna, to take legal measures to protect and manage wildlife, especially species which are endangered and to cooperate with and assist each other in all of these activities as well as in research and the protection of ecosystems.

In June 1976, the U.S. introduced a resolution at the General Assembly of the Organization of American States calling on the nation's to take steps to implement the convention's terms and make nature conservation a basic and active part of their development planning. This resolution which was drafted by the Interior Department draws attention to the fact that the renewable natural resources of the hemisphere are being exploited in an unplanned and destructive manner which, if continued, will result in their exhaustion and the degradation of the environment. It also draws attention to the effects of the use and spread of ecologically destructive pesticides and pollutants.

It proposes to reinforce the capabilities of the OAS to provide coordination and assistance in renewable natural resource management and research and to organize meetings of scientists, managers, and government representatives to review situations, develop measures and cooperative programs and to draw up accords binding the nations to agreed principles, practices, and regulation.

It would be a most appropriate and effective use of the Landsat program to make it work for the Convention on Nature Protection in the Western Hemisphere by helping to provide an overall ecological picture of the Hemisphere and an ongoing monitoring system by which we can observe the effects of development and pollution and detect changes for the worse in time to deal with them. I intend to work on this and similar uses of the Landsat during the coming year. Though national sensitivities will continue to cause problems, I believe that Landsat can be one of the most effective aids to ecological study and conservation, and that the countries once they see this, will lose their suspicion of it. In this regard I cannot stress too strongly that agreement among the participating parties on the mode of operation is imperative.

I would now like to turn to another topic. While many operational uses have sprung directly from the availability of global satellite observations and many others are "waiting in the wings" for operational commitments, scientific utilization of the data remains relatively, in its infancy. The reasons for this are understandable and predictable; they include:

1. the detection of Earth features that have never been seen before. Although most of man's progress has come from seeing new things, time is required to translate these observations into acceptable scientific fact;

2. the data provide a dynamic view of the Earth, heretofore unavailable. As with new features, time is required to adapt scientific educational, and management thoughts and procedures to achieve understanding of the scientific advantages of repetitive viewing;

3. the information unit of Landsat data is larger than information units in data commonly applied toward solution of Earth science problems. This requires significant adaptation by the scientific community before absolute gains and evaluations can be accomplished.

There is a rapidly growing body of evidence that suggests that there are very large linear and curvilinear features on the surface of the Earth (many previously unrecognized) that may be classed as fundamental structures that extend to great depths. What is the significance? For one, these features may exert control on the upward migration of ore-bearing fluids to the shallow depths of the Earth. For another, they may also have affected rocks at depth with resultant control of accumulations of oil and gas. Such linear features are best observed by satellites with their large aerial coverage.

The uniformity and global coverage characteristics and repetitive nature of the data foster scientific exchange and extrapolation among the scientific community, and, hence, significant scientific benefits may accrue in a shorter period of time than was anticipated.

The benefits go beyond the scientific community. New opportunities have been opened for international cooperation by the United States. Industry in the United States has a new tool for efficient exploratory work in the search for resources and engineering planning. International financial institutions have a source of data that assists them and the cooperating nations in assessing the validity of investments that are made.

The availability of Landsat and NOAA satellite data present man with a large and perhaps unique opportunity to better his scientific understanding of the current and historic mobility of the Earth's crust and the relationships of this mobility to emplacement of minerals and fuels.

Likewise, the repetitive nature of the data are providing new knowledge relating to interlinkages between the surface and subsurface of the Earth as they apply to a variety of disciplines. In an educational sense, it can be said that these data open a "whole new world" to the student, regardless of age or level of education.

Referencing this field of Remote Sensing to recent developments in the policy area, let us note the relevance of President Carter's principles of national energy policy to the requirements for improved data.

The President said in principle three: "We must protect the environment. Our energy problems have the same cause as our environmental problems--wasteful use of resources. Conservation helps us solve both at once."

The President said in principle nine: "We must conserve the fuels that are scarcest and make the most of those that are more plentiful. We cannot continue to use oil and gas for 75 percent of our consumption when they make up only 8 percent of our domestic reserves. We need to shift to plentiful coal while taking care to protect the environment, and to apply stricter safety standards to nuclear energy."

In summary, successful use and derivation of benefits from remote sensing systems is of course highly dependent on program continuity to ensure that the data will be uniformly collected over long periods of time to increase its value as an indicator of basic formations and of significant changes in our environment.

Several bureaus of the Department of the Interior are now moving toward uses of the experimental Landsat data products to meet their operational needs. A number of State agencies, commissions, and associations of States are including Landsat data into their ongoing State programs. The need for continuity of data and information concerning National program commitment by these Governmental organizations is critical for decisions related to incorporating this technology into ongoing programs to meet local, regional, National, and International needs.

I personally believe it is time for a rebirth of remote sensing. I believe we know enough about it to use this science wisely and for the benefit of mankind.

These recommended directions of approach may not make the substantive problem of conserving and using natural biological and mineral resources very much easier to deal with than it was before, but they have one genuine merit. They respect the crucial fact that the distinctive features of science lie not in the types of objects and events to which the scientist has access but in the intellectual procedures that his investigations employ. He must work within the community of man with man's support and favor.

Thank you.

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GATHERING AND USING INFORMATION ON A GLOBAL SCALE

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ABSTRACT

The paper will introduce the subject by discussing the importance of information gathered, integrated and analyzed over broad regions of the world. Means of acquiring information on critical areas will be outlined, and the particular role that remote sensing can play will be described in each case.

Following this introduction, the possible implementation of a global information system will be presented. Some of the current difficulties in initiation of such a system on an operational basis will be discussed. In this way, issues will be surfaced for consideration.

The importance of innovative leadership in a program to implement a global information system (hopefully on the part of the U.S.) will be highlighted, and some actions that the government might take, both in Congress and in the Executive Branch, will be suggested. The relationship of U.S. Government activities to international interests and to industry in carrying forward such a program will be discussed. The need to stimulate more private sector initiative and to transfer over time many responsibilities from government to commercial interests will be highlighted.

Lack of information or bad information haunts us in almost every facet of our daily lives. Last winter a natural gas shortage enveloped the eastern United States. Was it real or were the suppliers holding back? What are the longer term prospects? Apparently, nobody knows for sure, and as a result, the skeptical public lacks the motivation for individual sacrifices. A drought exists in the western United States. It is bad but how bad, and are the scarce water resources being managed efficiently to minimize the impact on the affected citizenry?

Most of us here know that in many areas of concern about resources and the environment, the technology developed in the space program and other advanced programs can be applied to achieve more effective gathering and use of critical data. Why is this not being pursued more aggressively? I will attempt to deal with this question, and I will make some suggestions as to how we can get started along the road to acquiring and applying better information than is being used today.

Although satellite observations of the earth already have proven to be of great utility, such activities have mainly been experimental in nature. In most instances, these outstanding capabilities have yet to be put together

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as a true information system. The word, "system" has been misapplied frequently to efforts much too immature and unsystematic. A system entails an orderly way of getting things done. Experimental capabilities, such as those which have been so successful using Landsat data, now need to be amalgamated in an orderly way into an efficient arrangement for their operational use.

Data requirements often extend to whole regions of the country, as in the case of the gas and water shortages just cited, or across the entire country, a situation applying to our generally diminishing known mineral resources. Indeed, with the highly interactive world society in which we now live, many things (food and environmental effects, for example), require information on a global scale. So at least in some situations, we should aspire to a global information system, and in many others, a system covering at least broad regions of the world.

Of course such systems might start small and where necessary become larger; but small systems cannot be made efficiently into large systems, without an approach that maintains an orderly way of getting things done. Certainly each of us as individuals, or each state as a part of this country, or each nation as a part of the world community, cannot operate in a compartmentalized sense and still expect to achieve this necessary order, or expect to get big things done, no matter how strongly or wisely we pursue our individual efforts. For the case we are considering here, we all need to work in the context of the demanding necessity for a broad information base for decision making.

With a recognition of this broad character of many of our informational needs, what is the best way of meeting those needs? I have already strongly suggested that in many areas involved with earth resources and environmental considerations this broad information base can best be achieved through the use of data gathered by satellites. In fact, such capabilities have been applied in an operational sense by placing weather satellites in synchronous orbit to provide warning of severe storms and tracking of major weather systems. Data from other weather satellites are used in numerical weather prediction in all regions of the world. Nimbus satellites monitor the changes in the life-protecting ozone layer high in the stratosphere. And Landsat has surveyed the world's land surfaces providing data used in crop production estimates, water resources management, mineral exploration, land use evaluations, coastal zone change evaluations, and map updating, amongst others. These and satellites such as SEASAT, now under development, can provide important coverage of the air, land and sea, acquiring data pertinent to many areas of resource and environmental concern. I cannot possibly do justice to these tremendous capabilities in the time allotted to me, but related papers being presented at this symposium, as well as those presented in past years at similar symposia and in papers published by NASA, NOAA, USGS and professional societies, can supply comprehensive background information.

There are other values that satellites bring to broad area data acquisition. Data can be updated rapidly and frequently, and are relatively easy to understand and relatively simple to integrate into common formats for general use, and although satellites do not usually produce all the data needed in each use area, other data sources can be employed to augment, while taking advantage of the broad coverage and rapid updating characteristics of the satellite. It is for these reasons that satellites seem to provide an excellent foundation for global information systems dealing with earth resource and environmental factors.

In spite of the obvious strong need for broad area information, the logic of the approach just outlined, and the strong support for this class of satellites by many sectors of the using community, the progress toward operational information systems of this kind has been painfully slow. Here are some of the reasons for this situation:

First, in some government circles a reluctance to support the creation of such systems has existed because in the past broadly based information systems have been characterized by a continuum of dominant federal government support, for example, weather information, agricultural reports. With this approach, the funding requirements place a burden on the general taxpaying public rather than on the direct users of the service. Although this approach may be logical in the cases of many socially oriented needs, it has been questioned in other areas, particularly in areas of Landsat data use.

Second, no individual federal agency has the clear responsibility in this area. The fact that many agencies are involved produces both positive and negative effects because even though many agencies strongly support the concept, when competing for federal funds all agencies tend to place priority on programs known to be included in their own charter.

The third point involves the other side of the activity, the role of free enterprise. Information systems of the type being considered here are associated with a very diverse and diffuse set of users. Such a market is difficult to aggregate, a condition which tends to stifle initiative from within the private sector.

These three conditions produce a kind of "Catch 22" situation. Nevertheless, these problems are real and they should be recognized and circumvented so as not to inhibit the implementation of systems for which there is such a demanding need in future years.

I feel that several things need to be done. An agency should be designated, or alternatively one created, to take the lead in implementing the initial phase of a global system to provide earth resources information based on Landsat and associated capabilities. In parallel with this activity, a plan should be developed to involve the private sector and to transfer to them over time as much of the effort as prudent, including responsibilities for financing. This action also will take advantage of the efficiencies and responsiveness that generally characterize free enterprise efforts. So at the outset, the responsibilities of the federal government will be dominant because most of the early financial burden will have to be borne by the government, but as the system evolves to one more capable of being self-supporting, the involvement of the private sector should increase. To help assure this trend, the private sector should have a meaningful early involvement, with government support where necessary. On the other hand, the activities of the government in this area will never cease entirely, partly because of a continuing and expanding use of the data by federal agencies and partly because of a need for a continuing oversight function. However, in carrying out their functions, government agencies should, where practical, contract for needed support rather than building up in-house capability, and in particular, government should avoid unnecessary competition with the private sector. I suggest that some new working relationship might be developed between government and industry which takes advantage of the strong points and positive values of each. Perhaps some innovative thinking is needed on this subject.

To digress from this line for just a moment, perhaps a question has arisen as to why this system, with its strong international values, should not be financed and operated by an international organization, an agency of the United Nations, for example. Although many might feel that this arrangement would be appropriate from a theoretical standpoint, the practical problems of organization and financial support just discussed for one nation are greatly compounded because of the multitude of nations potentially involved, each with its own interests and objectives. Such considerations lead to the conclusion that the system should evolve from a national program or a set of national programs. These programs, through bilateral or multilateral or international agreements, should serve the needs of all nations and the international community in general. Hopefully many nations would contribute materially to the overall system, including deployment of data acquisition systems.

A very successful precedent exists for this approach. The world meteorological community is the example. Most of the worldwide capabilities have been developed as national programs, but the World Meteorological Organization, which has access to the data, formulates its own programs around these capabilities in a way which efficiently serves the international community. For example, the United States has developed a series of synchronous Meteorological Satellites to provide storm warning and other services to its environs. These services have also been provided to other parts of the Western Hemisphere and these satellites have also played an important role in major WMO programs. Shortly Japan, the Soviet Union, and western Europe will be joining in this operation with similar satellites, to form a continuous observation belt around the world. Coordination by the WMO has assured that the data formats of all these satellites will be common. The data will be exchanged and used by many nations in major WMO programs.

Returning now to a further discussion of the global system for earth resources information, its initial configuration and its evolution might correspond to the description which follows. Although a substantial number of satellite types and other data sources can be envisioned as comprising the ultimate version of this global information system, the early system should probably be of a simpler form. As previously implied, a companion system already exists in the operations of the National Environmental Satellite Service of NOAA in the provision of weather information. However, it appears to me that information about the earth's land surfaces should be the primary basis for the system, for land is where most human activity takes place, land is where most of our resources are presently found, and land is where human impact is greatest and most dynamic. This leads to the conclusion that a system based initially on Landsat capabilities, while using satellite weather data and other applicable data, is a very good way to start. The extensive uses of Landsat data which have been experimentally verified provide strong support to this position. Of all these uses, the areas of food, water and mineral resources might be the primary emphasis areas of the early system.

Remember, that with proper structuring, other capabilities can be included by building on this initial capability. Hopefully, data will be acquired from many sources by all appropriate means. With this idea in mind, it is easy to visualize that the key element of this system is the one concerned with the function of data product production and distribution. The retailer of the data would provide products on demand to all customers at fair prices. The outlet or outlets would probably start with a standard set of data products but might also stock and sell appropriate ancillary data (correlated weather data, for example). I personally feel that this function, in an operational sense, should be concerned solely with the provision of data packages and should not provide information extraction services. The latter should be accomplished by the customer or someone the customer hires for this purpose. Nevertheless, the data production and dissemination element must have a research effort pertaining to information extraction, in order to anticipate and be responsive to the particular data needs of the various customers. These customers could request various formats, packaging or ancillary features as required. Such requests would be evaluated as to possible existing data sources, as to whether new data should be obtained and whether a new data acquisition system should be procured and the cost of any potential augmentation. New data sources in the experimental stage or just coming on line (for example, Seasat) would be evaluated for applicability. In this way, the product line could be expanded as the need arises and as the capabilities become available but only when warranted considering value versus cost. In order to maintain the activity at a scope commensurate with effective management, certain restrictions on the effort would appear prudent. As already stated, the effort would be limited to earth resources information. Possibly it also should be limited to areas where satellite data plays a dominant role. Such guidelines can be established at the outset of the implementation activity.

I am sure the scenario just described sounds to many of you very much like what is taking place today. Landsat satellites are flying and acquiring data every day. This data is being processed, reproduced and distributed to consumers, many of whom are involved in information extraction activities; however, these activities are mainly experimental in nature and it cannot be otherwise until certain changes are made. A number of important differences exist between an experimental and an operational system, which must be recognized. Most importantly, once committed to an operational mode, reasonable assurance of continued availability of the data is an absolute necessity. This particular consideration involves a number of factors.

First, the data service cannot "dry up" as a result of equipment failures. Therefore, adequate backup or redundancy of ground and satellite equipment is necessary. In this context the new Landsat D initiative of NASA, for example cannot be regarded as a significant step toward an operational system, for even though a single backup has now been included, this capability does not provide adequate assurance of continuity of the service.

Second, in an operational system, changes substituting improved equipment can be made only after such equipment has been fully demonstrated as to its overall servability, and then only after the customers are in a position to use the new capability. Again using Landsat D as an example, the elimination of the current Landsat instrument, the Multi-Spectral Scanner, from the payload places the satellite strictly in an experimental category, for the new instrument, the Thematic Mapper, is untested and no customer has yet had experience with its data.

Third, the overall system must have a response time compatible with user needs. No real good comes from providing operational data at one-month intervals if the users require receipt at one-week intervals. Along the same line, if a user needs data within one week after acquisition, it cannot be delayed by one month in the processing. Improvements in the timing of Landsat data availability are feasible and are definitely needed for an operational system.

Finally, the institutional arrangements for the support of an operational system have not been clarified. One other feature of many operational systems must also be emphasized. A practical degree of "pay as you go" is highly desirable in the long term. The planning should provide concrete evidence that this is an objective.

Returning to the Landsat D question for a moment, I am not critical of it at all as a fine new experimental spacecraft. The Landsat program is in an early stage of evolution and major improvements can be expected over the next several decades, but a truly operational capability could have been incorporated with great facility right along with the experimental capability, and this should still be done. I think most of the people directly involved with the program feel as I do; however, both government and industry personnel must avoid getting so enthralled with the new developments that the real purpose of Landsat is lost. That is, to serve as the foundation of an operational information system which will help eliminate lack of information problems so prevalent in today's world and to contribute in a major way to solutions to some of our difficult earth resources and environmental problems.

In concluding these remarks, I wish to emphasize that space is not just a place for scientific investigation and exploration, important as these activities may be. Space systems have already demonstrated great ability to directly enhance the well-being of all the people here on earth. We know this to be true in the areas of satellite communications, weather prediction and storm warning because highly effective systems are now operating worldwide. Similar contributions can be achieved in the areas of concern which pertain to earth resources and environmental effects. Let us all get on with the job of making it happen.

U.S. INITIATIVES FOR REMOTE SENSING
APPLICATIONS IN THE DEVELOPING WORLD

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I would like to endorse what the earlier speaker said about space not simply being a scientific playground. At the risk of being critical, I would like to share some thoughts about what a political-bureaucratic beastie like me sees when he comes to talk to technical beasties like yourselves.

I know your mother told you not to consort with us political and bureaucratic types, but bear with me for a few moments because I do believe we have something in common. Because what I have been engaged in for the past year has been basically the creation of a market for what you people are all about. And to reiterate what I said a moment ago, it is important in the creation of that market that space not simply be a place for scientific endeavor. You must find a way to tell the rest of the world what it is you are doing and answer that famous question, "So what?".

When there is a scientific experiment and the layman comes in and asks "what are you doing?" you must tell him more than the humas is doing guzziwhat because he doesn't know what a humas is and doesn't care about a guzziwhat. He does care if it grows more food. He does care, in particular, if it allows him to be elected next year. He does care if it means more slots in his particular office. And I urge you, despite the fact that you consider those unclean concerns, you had best engage in them because that is how we put rice in your bowls.

It was about two years ago that the administrator of AID decided that I had harassed the international oil industry sufficiently over at the Federal Energy Administration and told me to come back. He said look over what we in AID have been doing in our space efforts here. We were the pioneers, we were in the business of supporting remote sensing way back in 1970 already. Why is it that it hasn't gotten any farther in the LDCs than it has?

We in AID are primarily interested in how do you get to that huge body of potential users called the developing countries. After all, to those of us who are students of remote sensing it is self-evident that it is more valuable in those countries than in the developed countries because it does things for which there is no substitute. We were curious, why is it we haven't gotten farther with this?

Well, I am an economist by training. We think of the problems in terms of markets. That means you must have many buyers and sellers. You must have relative ease of access, and you must have a free flow of information. Well, we didn't have the many buyers and sellers that are needed in order to give you the kind of constituency you must have if you are going to have an operational Landsat program. The reason we didn't and don't have that is because access to your discipline for the people in the developing countries is difficult. More important, you do not have the critical mass of users because there is very little information of a practical sort available in a form that it can be used politically when one goes to the Bureau of the Budget and says, "give me money" No matter how virtuous you are, if you can't do that you are not going to do anything, you are going to get shot down. Well, that was a very interesting problem. How do you go about solving it.

We had a serendipitous occurrence. NASA's ATS six communication satellite was being moved from its station over Africa to a new station over the Pacific. The Administrator asked me to investigate the possibility of using the satellite for demonstrations in LDCs. The reply was, yes if we move very fast. We decided to do a series of demonstrations which would create the beginnings of a "market" in the developing countries which in turn would allow for accelerated applications of space technology. That condition in turn should expand the constituency in the United States and elsewhere for an operational Landsat system. Fundamentally that is what our program called AIDSAT, AID Space Age Technologies, was all about (as it pertains to remote sensing).

What do you have to do if you want to accelerate the use of these technologies? First, and foremost, you must start talking to a different audience. You might start talking to the political and decision-making communities of the developing countries, because they, like the communities in our own country, are unaware of what a huzza is and don't care about a hoza-what. You must articulate in political terms to decision makers what it is you are doing, and thereby make the technical people respectable when they come in and place demands on scarce resources. You must get their attention and show them the state-of-the-art.

We set out to do this with the AIDSAT program. We decided that we would put on a series of demonstrations of applications of space technologies in developing countries, in as many places as we could. We settled on 27 countries plus a conference on science and technology applications (CASTARAB) for ministers from all of the Arab states. That was a real stroke of luck; they happened to be in Rabat when we were there and we put on the demonstration for them as well.

Three films were made from concept to completion in four languages in 73 days. If you have ever made a film and shot it on four continents you know what kind of a time schedule that was. One of those films is going to be shown today, "Images of Life". That film, by the way, has won two gold medals and a bronze medal. It is not designed to tell you, in the technical community anything. You know everything that is in that show. It is an example, however, of how you get through to the decision makers on a technical subject. It gives them an idea of what it is you people are all about and suggests to them that remote sensing might even be a respectable thing to spend some money on. There are two companion films, one on communications applications in developing countries, "If One Today, Two Tomorrow", and "Survival", which is on disaster prediction assessment and relief.

These films are available for showing on request from AID for short periods of time. Those from other countries should contact the U.S. Information Agency in their capital. The films are available in English, French, Spanish and Arabic.

Well, what do you do beyond simply making films and showing a program? You need a "grabber", because you are after the front office of these countries. You want the decision makers as I said before; so we asked President Ford to film an introduction to the program. He consented, and incorporated with it a bicentennial greeting.

In terms of hardware, we had three complete sets of transmit and receive equipment for the ATS 6 communications satellite to do live color broadcasts to and from the capitals of these countries as well as two to three remote areas in the host country. A DC-8 stretch; leap-frogged the equipment sets one over the other. The extreme simplicity, low cost, and transportability of the ATS 6 ground terminals and associated equipment was thus dramatized.

We had a two hour and fifteen minute show in each country. It began with an astronaut, live, introducing the President, who then gave the greeting and the introduction. This was reciprocated by the chief-of-state in 15 of the countries and by various senior people in the rest. The astronaut then did live bridges among the three movies. Thereafter the program then went into a discussion by

a panel, (usually ministerial level in the host countries) of the applications of space technologies to their development problems. Finally, there was the grand slam; live, two-way color video between Goddard Space Flight Center in Greenbelt, Maryland, and the country where we were. A panel in the U.S. answered questions of the panel in the host country. That was it.

We also learned quite a few things. I was told that space had a great number of political problems which were so profound and so disturbing to the governments of all of these countries, that we would probably not be welcome anywhere. The fact that we were using something that could be called a direct broadcast satellite was the equivalent of living in sin. The unauthorized overflight issue on Landsat, which is a great source of heat if not light in certain debating circles, was another problem which I was told would stand in the way of country acceptance of the AIDSAT demonstration.

In fact, no one in any of those countries raised those questions. Not one.

After all, we had the real item, we had a real and serious commitment, we had some things that people could really use. And when you do that, the philosophers are invited into the next room for cigars and brandy and a different group of citizens appears. And they are not really terribly concerned about all of those matters. I am not saying that direct broadcast and satellite overflight are not real issues, nor am I saying that they should not be resolved. But I am saying that we should not allow a theoretical political debate to inhibit us in the applications of these technologies.

What did we find? First of all, we found what we expected; most people really didn't have the foggiest idea of what all of this was about. In that regard people in developing countries are not much different from people in the U.S. After all, people in this country haven't had an opportunity to really see in the very practical simple sense what it is that the space community is doing either. There was great amazement at the simplicity of some of the applications; great amazement of how cheap some of the applications were, and finally, a good deal of positive surprise that there was a real willingness on the part of the United States to make this resource available.

Other things that we found: We found that the information systems on remote sensing experiments which the earlier speaker mentioned is just plain awful; that is the only way to describe it. The best way to find out how bad the information system is on applications in developing countries is to go out and make a movie on the subject. You will find yourself chartering helicopters to photograph nothing. There are experiments on the books that have never occurred, and there are experiments that have occurred that are not on the books. And if you go out you will find large numbers of people patiently reinventing the wheel simultaneously. That is an enormous waste of time and energy.

I would urge that this community begin thinking very carefully about the genuine need to establish an effective, simple remote sensing information system for the developing countries as well as the more sophisticated procedures that you are using here. It is very, very important if your resource, that I personally consider to be valuable, is not to be squandered in the developing countries. It is very important if you are to expand the community of users, and thereby expand the rationale for an operational Landsat system. And I point out to you once again, an operational Landsat system is a political problem, it is not a technical problem and it is not an economic problem. I always chuckle when people tell me there is no money in the budget. Nonsense. How on earth can you have no money in a budget of 440 billion dollars. It is crazy on the face of it. What people are telling you is that you have no priority. And the reason you have no priority in all that nice green money is because you haven't told anyone why you should have a priority. That task requires immediate attention. An integral part of that effort is making the remote sensing community in LDCs more efficient by developing the simple information system that allows them to benefit from one another's experience and to communicate with one another in an effective manner.

What are some of the other results? We went from three million dollars a year to 14 million dollars a year in our efforts for applications of space technology in the developing world.

We stimulated the thought, -- the governments, -- the decision makers in these countries to the point where our requests for assistance in remote sensing and in communications have increased ten-fold. These are bureaucracies that have made these requests in a matter of months and anyone who has ever dealt with bureaucracies can only sit down and marvel at the speed with which these requests have arrived. In short, I believe that we have basically accomplished what we set out to do. We have begun the creation of the "market" in the developing countries for remote sensing. The ball is now in your court.

I am enormously pleased that this symposium is going to Manila next year, I consider it to be an eloquent statement on the part of the remote sensing community that it has accepted the challenge of expanding its numbers to incorporate people from the developing world. Moreover, I see it as a recognition by this community of the need to address the very special concerns in the developing countries and to expand that constituency. Let me urge you to continue your global perspective; your resource is global, think of yourselves as having a global charter, avoid the temptation to be parochial, and for goodness sakes don't let your budget drive your dreams. Thank you very much.

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THE PRESENT STATUS OF REMOTE SENSING IN THE UNITED NATIONS (April 8, 1977)

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I. INTRODUCTION

Problems arising from remote sensing of the earth by satellites have been the subject of indepth research and analysis by the United Nations. Every aspect of this multidisciplinary subject has been explored in more than 100 reports and papers published as UN documents dealing with all the implications of remote sensing: scientific, technological, institutional, political, economic, cultural, and legal. National, regional and international situations have been analyzed, and the General Assembly has passed resolutions requesting that the Committee on the Peaceful Uses of Outer Space give a high priority to remote sensing. The identification and analysis of issues has been going on for several years, the objective being international agreement on general principles to guide nations in the conduct of their remote sensing activities.¹

II. UN ORGANIZATIONS CONSIDERING REMOTE SENSING OF THE EARTH BY SATELLITE

The UN Committee on the Peaceful Uses of Outer Space has two subcommittees: the Scientific and Technical and the Legal Subcommittee. All three bodies are composed of the same membership which is representative of 37 nations. Each year the subcommittees meet separately and send their reports to the parent Committee whose final action is an annual report to the General Assembly. An effort is made to coordinate the work of the two subcommittees because of the interaction between their findings and recommendations. The Outer Space Affairs Division serves the Committee and publishes research reports on space problems. When the General Assembly receives the Committee report, a resolution may be passed giving directions for future work. The resolutions may embody the agreed text of a draft treaty to be recommended to States for ratification.

The subcommittees, particularly the Legal Subcommittee, have adopted the practice of establishing Working Groups on specific problems, and occasionally the working groups create mini-working groups to deal with especially knotty problems with a view toward achieving agreement among the members.

III. METHOD OF WORK

From the time the Committee on the Peaceful Uses of Outer Space was established, it has been the practice to conduct its work in such a way as to reach agreement without the need for voting.² This method, which also applies to the two subcommittees, requires the formation of a consensus among all members in order to reach agreement. Any one nation can prevent agreement by its sole opposition.

This method has proved to be remarkably successful as demonstrated by its use in formulating four space treaties which are now in force: (1) the Treaty on Principles Governing the

¹Space Activities and Resources. A review of the activities and resources of the United Nations, of its specialized agencies and of other competent international bodies relating to the peaceful uses of outer space. United Nations, New York, 1977. United Nations document A/AC.105/193. 251 p.

²International Cooperation and Organization for Outer Space. Senate Committee on Aeronautical and Space Sciences. 89th Congress, 1st session. Senate document No. 56. August 12, 1965. 580 p. See the sections of the document on the history of the UN Committee on the Peaceful Uses of Outer Space; see also the list of UN resolutions.

Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, October 10, 1967; (2) the Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space, December 3, 1968; (3) the Convention on International Liability for Damage Caused by Space Objects, October 9, 1973; and (4) the Convention on Registration of Objects Launched into Outer Space, September 15, 1976.³

Achieving a consensus takes time but results in a firm foundation for international space law. A consensus can be achieved more quickly if an issue is presented with sufficient margin on either side to permit negotiation and a narrowing of different points of view concerning proposals for solving problems. If an issue is introduced in irreconcilable terms, however, it is difficult and time-consuming to reach agreement. Decisions by voting might appear to be quicker in certain circumstances, but would not be a method which could solve irreconcilable positions because nations with active and expanding space science and technology programs would not agree to their national programs being curtailed or eliminated by decisions of other countries. There is a growing number of nations engaged in space applications beneficial to all countries and they have been abiding by the 1967 Treaty on Outer Space which provides that "Outer space, including the moon and other celestial bodies, shall be free for exploration and use by all States without discrimination of any kind, on a basis of equality and in accordance with international law, and there shall be free access to all areas of celestial bodies." (Article I, paragraph 2.)

Another feature of the method of work of the subcommittees is that representatives seek, in connection with remote sensing principles, to find "common elements" on which they can easily agree, and then translate these eventually into "principles". This is not necessarily the negotiating process for all principles, but it is often used for difficult problems. When a principle is identified, it may then be subject to differing points of view and these are indicated by square brackets around the words in question. The identification of a principle, even when it includes square-bracketed phrases, is valuable to the negotiating process of consensus because not only is the subject set forth in a clear manner, but also the areas of agreement and disagreement are clearly identified. On such a basis it is easy to determine exactly where more discussion must take place before consensus can be reached.

IV. SUBCOMMITTEE SESSIONS IN 1977

The purpose of this report is to explain the results of the work of the two subcommittees on remote sensing of the earth by satellites during their 1977 sessions. The Scientific and Technical Subcommittee met at United Nations headquarters in New York from February 14 to 25, 1977. The Legal Subcommittee also met at the United Nations from March 14 to April 8, 1977. The reports of these subcommittees will be considered by the full Committee on the Peaceful Uses of Outer Space when it holds its 20th session in Vienna in June 1977.

V. SCIENTIFIC AND TECHNICAL SUBCOMMITTEE (FOURTEENTH SESSION)

The Subcommittee had available 36 documents on various aspects of its work, many of them concerned with remote sensing. Questions relating to remote sensing were given first priority and the Secretary-General had submitted four studies pertinent to this work:⁴

1. Feasibility study on a possible coordinating function for the United Nations in future operational activities in remote sensing from satellites: revised concept (A/AC.105/154/Add.1 and Corr. 1-3);

³Space Law: Selected Basic Documents. Senate Committee on Aeronautical and Space Sciences. 94th Congress, 2d session. Committee print. December 30, 1976. 464 p. (This committee has been transferred to the new Senate Committee on Commerce, Science and Transportation where the functions are performed by the Subcommittee on Science, Technology and Space.)

⁴Report of the Scientific and Technical Subcommittee on the Work of its Fourteenth Session. UN Committee on the Peaceful Uses of Outer Space. March 1, 1977. A/AC.105/195. p. 7.

2. Information concerning existing or planned national or regional ground stations for direct reception of remote sensing data from satellites (A/AC.105/155/Add.4-6);
3. Available studies, reports and other material relevant to the consideration of remote sensing from satellites (A/AC.105/176);
4. Information concerning the activities of Member States and international agencies in launching remote sensing satellites (A/AC.105/178).

In addition, the Subcommittee had a number of proposals and working papers.

Lack of a clear definition of "data" and "information" to apply to remote sensing was considered a problem because of its implications for developing technology, institutions and law. The Working Group of the Legal Subcommittee had previously interpreted "data" to mean raw products and pre-processed products coming from the satellite, while "information" was to mean "analyzed results." The Scientific and Technical Subcommittee considered these definitions somewhat ambiguous and advised that "data" be changed to "primary data" and "information" changed to "analyzed information." The Working Group of the Legal Subcommittee could then make the following changes in the definitions:⁵

1. The term "primary data" means those data which are acquired by satellite-borne remote sensors and transmitted from a satellite either by telemetry in the form of electro-magnetic signals or physically in any form such as photographic film or magnetic tape, as well as the pre-processed products derived from those data which may be used for later analysis;
2. The term "analyzed information" means the end-product resulting from the analytical process performed on the primary data combined with data and knowledge obtained from sources other than remote sensing satellites.

These definitions are considered applicable to the present state of the art of remote sensing technology, and they may require re-examination in the future if technology advances.

There was considerable discussion of spatial resolution and the possibility of using it as a basis for solving problems such as those arising from the request of some nations for their permission prior to being remotely sensed. Some delegates thought that regulation could be based on degrees of clarity of sensed data. The USSR proposed a division into categories of "global", "regional", and "local" as a basis for distinguishing between open dissemination and dissemination requiring permission. Agreement could not be reached on whether spatial resolution was necessary or desirable as a basis for international regulation. The Scientific and Technical Subcommittee realized that the Legal Subcommittee needed more information before deciding "what, if any, should be the limitations on dissemination of primary data without the permission of the sensed country."⁶ The conclusion was to suggest that the Secretariat make such a study to be discussed at the Subcommittee's 1978 session. There was agreement by the Subcommittee that "there was no scientific or technical basis for a sensed State not having timely and non-discriminatory access to data of its territory."⁷

Attention was given to existing and planned space and ground segments for remote sensing. Experimental remote sensing programs using satellites are now being conducted by the United States, India, the USSR, the European Space Agency and the German Democratic Republic. The Subcommittee noted that the Soviet Union was ready to extend dissemination of all available

⁵ Ibid., p. 9.

⁶ Ibid., p. 9.

⁷ Ibid., p. 11.

remotely sensed data to all interested States and that to this end the Soviet Union was prepared to cooperate with interested States bilaterally or multilaterally in carrying out remote sensing of their territories from space and providing them all the data obtained, including photographic material with spatial resolution of 50 metres and finer."⁸ The Subcommittee concluded that remote sensing systems would become operational. In fact, it is upon this assumption that intensive research and analysis is being conducted within the framework of the United Nations.

Success of the LANDSAT data and information and its worldwide use resulted in the development of the ground segment with receiving stations established in Brazil, Canada, Italy, the United States and others planned in Argentina, Chile, and Iran. Japan, Sweden, Upper Volta, and Zaire are considering establishment of such a station. The Subcommittee emphasized the importance of regional collaboration and called on nations to examine the feasibility of establishing their stations on a regional basis.

It was pointed out that several nations, specialized agencies and international organizations had cooperative programs with the UN for education and training facilities. A comprehensive list was available for training facilities and courses in remote sensing for participants from developing countries.⁹

Finally, the coordinating role of the United States was recognized in training and technical assistance. The UN role in education, exchange of information, and informing nations about remote sensing activities develops through the Committee on the Peaceful Uses of Outer Space, its subcommittees, the Outer Space Affairs Division and the specialized agencies.¹⁰

The Subcommittee recommended that the Food and Agriculture Organization strengthen its center in the field of renewable resources and also that a center be established in CNRET for non-agricultural resources with four suggested main functions:

1. To catalogue, store, and interpret remote sensing data, providing facilities for examination by interested parties;
2. To circulate available information and to direct requests by countries for remote sensing data to proper sources;
3. To provide impartial advice and assistance to technical assistance projects, Member States and United Nations bodies;
4. To organize specialized training courses for users, managers and decision makers.

Some thought was also given to the idea of setting up a third center in a developing country if one should be needed, although this action would require feasibility and cost benefit studies.

VI. LEGAL SUBCOMMITTEE (16th SESSION)¹¹

When the Legal Subcommittee adjourned on April 8, 1977, the results of its Working Group III on Remote Sensing consisted of eleven draft principles and, tentatively, the possibility of an additional principle. The eleven principles with their square brackets indicate the issues which have been under discussion, the degree of consensus and the areas of disagreement. If the practice followed in previous years is again adopted, it is likely that the parent Committee's report, following its June 1977 session in Vienna, will contain the principles

⁸Ibid., p. 12, 13.

⁹UN document A/AC.105/191.

¹⁰Report of the Scientific and Technical Subcommittee, *op cit.*, p. 16.

¹¹Report of the Legal Subcommittee on the Work of its Sixteenth Session March 14 to April 8, 1977. Committee on the Peaceful Uses of Outer Space. A/AC.105/196. April 11, 1977. (The author was appointed Observer by the International Astronautical Federation to represent the IAF and attended the 16th session.)

drafted by the Legal Subcommittee, although this presumption should be checked after the Committee's report is published. Between now and 1978, we can assume that the basis for international consideration of remote sensing of the earth by satellites will include the following draft texts, each of which is briefly commented upon.¹²

Draft Texts of Principles on Remote Sensing of the Earth by Satellites

Principle I

Remote sensing of [the natural resources of the earth] [and its environment] from outer space and international cooperation in that field [shall] [should] be carried out for the benefit and in the interests of all countries [mankind], irrespective of their degree of economic or scientific development, and taking into consideration, in international cooperation, the Particular needs of the developing countries.

This principle is in conformity with the 1967 Treaty on Outer Space. The issues are whether or not international space law should apply to remote sensing on a voluntary or compulsory basis; whether remote sensing should be considered to apply to natural resources of the earth or to natural resources and also the earth's environment or perhaps to some additional objects sensed with finer resolution. Another issue is whether remote sensing (after it is defined and/or delimited) should apply to nations or to all peoples.

Principle II

Remote sensing of [the natural resources of the earth] [and its environment] from outer space [shall] [should] be conducted in accordance with international law, including the Charter of the United Nations and the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and other Celestial Bodies.

This principle contains some of the same issues as those discussed in the comments on Principle I. On the agreed text, that is the text not in brackets, the principle is in conformity with other space treaties already in force.

Principle III

1. States carrying out programs for remote sensing of [the natural resources of the earth] [and its environment] from outer space [should] [shall] promote international cooperation in these programs. To this end, sensing States [should] [shall] make available to other States opportunities for participation in these programs. Such participation should be based in each case on equitable and mutually acceptable terms due regard being paid to elements...

2. In order to maximize the availability of benefits from such remote sensing data, States are encouraged to consider agreements for the establishment of shared regional facilities.

The square-bracketed words indicate the necessity of coming to agreement on exactly what is to be included in remote sensing; that is, precisely what is to be regulated or controlled internationally, and whether the problems are to be met by mandatory or voluntary responses. There is consensus concerning States having opportunities to participate in remote sensing programs, a principle which should appeal to nations which do not have remote-sensing capabilities. All the elements have not been set forth, but there is agreement that States should come to mutually agreeable terms and that matters be handled with equity. There is real recognition of the desirability for regional remote sensing facilities and this represents an advance over the first discussions which took place several years ago.

¹²Ibid.

Principle IV

Remote sensing [of the natural resources of the earth] [and its environment] from outer space [should] [shall] promote the protection of the natural environment of the earth. To this end States participating in remote sensing [should] [shall] identify and make available information useful for the prevention of phenomena detrimental to the natural environment of the earth.

Continuing the lack of agreement on whether nations must comply with the principle or can use their own judgment in each case, this principle identifies the value of protecting the earth's natural environment and preventing phenomena deemed detrimental.

Principle V

States participating in remote sensing of [the natural resources of the earth] [and its environment] from outer space [should] [shall] make available technical assistance to other interested States on mutually agreed terms.

There was no difficulty in agreeing to mutually agreed terms on making technical assistance available to interested States. Such assistance has been available for some time. However, the issue of exactly what is to be included in remote sensing, intended for regulation, continues to be undecided.

Principle VI

1. The United Nations and its relevant specialized agencies [and the International Atomic Energy Agency] [should] [shall] promote international cooperation, including technical assistance,^a and play a role of coordination in the area of remote sensing of [the natural resources of the earth] [and its environment].
2. States conducting activities in the field of remote sensing of [the natural resources of the earth] [and its environment] [shall] [should] notify the Secretary-General thereof, in compliance with Article XI of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies.^b

While agreement was reached that the UN and its relevant specialized agencies promote international cooperation and technical assistance, agreement was not reached on including the International Atomic Energy Agency, nor was agreement achieved on whether the UN was required to perform this function or could do it on a voluntary basis. The question of defining remote sensing and to what it applies remained unsolved. With regard to technical assistance, the Working Group added a footnote (a)--"Depending on whether the Subcommittee believes that a separate principle should be developed on technical assistance." This option is left open for future decision.

The second paragraph leaves some additional matters unsolved. Although agreement was reached on notifying the Secretary-General, only the 1967 Treaty on Outer Space was mentioned whereas the 1975 Convention on Registration of Objects Launched into Outer Space also has provisions concerning notification to the Secretary General. It may be that other space treaty provisions will be added in future sessions of the Legal Subcommittee. Footnote (b) in the text of the principle, provides that "The question of application to international intergovernmental organizations will be considered later."

Principle VII

Information^c obtained by remote sensing [of the natural resources of the earth] [and its environment] indicating an impending natural disaster shall be disseminated^d as promptly as possible to those States likely to be affected.

This principle has two qualifications in footnotes. First, "information" is "subject to later discussion of the terms 'information' and 'data'." Second, after "disseminated" a footnote has been added to the effect that the matter is "subject to further discussion after information concerning procedure of dissemination in the practice of the United Nations is received from the Secretariat."

Principle VIII^e

Taking into account the principles I and II above, remote sensing data or information derived therefrom [shall] [should] [not] be used by States [to the detriment of] [in a manner compatible with] the legitimate rights and interests of other States.

There is a question about whether this principle should be stated positively or negatively. Some nations want remote sensing data and information not distributed to the detriment of States while others see great difficulty in implementing this general statement and desire that the idea be expressed positively; that is, use of remote sensing "in a manner compatible with the legitimate rights and interests of other States." If the use were according to legitimate rights and interests, proponents think it could not be to the detriment of a State. There are many different concepts of what constitutes "detriment", and it is possible that the same data and information could be considered detrimental by one State and beneficial by another. This entire principle is subject to a footnote (e) which states that it "should be considered in connection with the formulation of a principle on dissemination of data or information and subject to later discussion of the terms 'information' and 'data'."

Principle IX

States participating in remote sensing [of the natural resources of the earth] [and its environment], either directly or through relevant international organization [shall] [should] be prepared to make available to the United Nations and other interested States, particularly the developing countries, upon their request, any relevant technical information involving possible operational systems which they are free to disclose.

The unsettled issue of precisely what remote sensing is to include for purposes of regulation continues in this principle. This principle seeks wide dissemination of information on possible operational systems, perhaps expressing the anxiety of some States that an operational system might be established without their knowledge. The coordination of this principle with space law provisions already provided in other treaties with regard to notification of the United Nations has not yet been worked out.

Principle X

States [shall] [should] bear international responsibility for [national] activities of remote sensing [of the natural resources of the earth] [and its environment] [irrespective of whether] [where] such activities are carried out by governmental [or non-governmental] entities, and [shall] [should] [guarantee that such activities will] comply with the provisions of these Principles.

This principle is taken from a provision in the 1967 Treaty on Outer Space and is related to other space law treaty provisions. However, it is not decided whether compliance by States after ratification should be mandatory or voluntary and whether remote sensing is concerned with the earth's resources and possibly also its environment or could include additional categories. The responsibility of a State for non-governmental entities engaged in remote sensing activities is also in question.

Principle XI

A sensed State [shall] [should] have timely and non-discriminatory access to data obtained by remote sensing [of the natural resources of the earth] [and its environment] from outer space, pertaining to its territory on reasonable terms [to be mutually agreed upon with the sensing State] and to the extent feasible and practicable, [shall] [should] be provided with such data on such terms [on a continuous and priority basis] [and in any case no later than any third State].^f

This principle reveals the number of issues difficult to resolve. Sensed states would like to have data and information on their territory, some would like to deny such information to other states or obtain it on a priority basis before other states. Some wish to make the arrangements voluntary while others want them compulsory. Some states wanted the data and information without mentioning "reasonable terms" while others could not agree to giving away such services without compensation. Although there is no difference of opinion about "non-discriminatory access," there is some lack of recognition of the technological and practical factors involved in "feasible and practicable"; that is, some States might wish the law to provide for acquisition and dissemination of data without considering economic and technological factors essential in implementing such a general idea.

^f"Subject to review in the light of the discussion on access by third States."

* * *

A very unusual situation developed with regard to the attempt to draft an additional principle and place it in the text after Principle XI. Some agreement had been reached on the wording but several delegations objected strongly to including the text under the word "principle". Finally, a compromise was worked out so that the text was set in what appears to be the four corners of a frame, and the reader is cautioned to see paragraph 13 of the Working Group III report. The matter is reproduced as follows:

Principle ... (see para. 13 of this report)

Without prejudice to the principle of the freedom of exploration and use of outer space, as set forth in article I of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and other Celestial Bodies, remote sensing [of the natural resources of the earth] [and its environment] [should] [shall] be conducted with respect for the principle of full and permanent sovereignty of all States and peoples over their own wealth and natural resources [with due regard to the rights and interests of other States and their natural and juridical persons in accordance with international law] [as well as their inalienable right to dispose of their natural resources and of information concerning those resources].

Paragraph 13 refers to this text as "a possible draft principle," and the report indicates that "This text is thus set forth wholly within special brackets in appendix A to this report for the reason that some delegations felt that an unagreed text should not be included in appendix A." This compromise was worked out at the last moment before the Working Group was required to report to the Legal Subcommittee. This entire matter reflects the fear of some States that remote sensing might be used as a technique to get control over their natural resources, and the position of other States that while there is sovereignty over natural resources it does not extend to information; and other delegations considered the matter was not relevant to remote sensing and should not be a principle, especially since there was no agreement on a common element.

The Legal Subcommittee did not take action on the definition of "primary data" and "analyzed information" provided by the Scientific and Technical Subcommittee, citing a lack of time as the reason. The information was provided for the report, however, in a proposal made by Sweden.

It should be noted that the first five principles had been identified and listed in 1976 and at the 1977 session the remaining six were formulated.

VII CONCLUSIONS

1. Remote sensing of the earth by satellites creates problems of institutional and legal arrangements which are much more difficult to solve than those of space communications by means of INTELSAT and the International Telecommunication Union; or space meteorology with the U.S. National Oceanic and Atmospheric Administration (NOAA) and the World Meteorological Organization (WMO). Although space communications and meteorology were difficult, each has a distinctive and identifiable character connected with known requirements for communications and weather information already in existence before space technology was added as a new tool. The results of remote sensing data and information can be used in a variety of ways and there is no single category of users which can be organized and regulated easily. The use of remotely sensed data and information also arouses fears of its abuse in the minds of leaders in some countries, fears that their natural resources will be exploited by others before they have an opportunity to develop them. Such fears, expressed in terms of nationalism, tend to create currents against the kind of international cooperation which has been the natural pattern for communications and meteorology. The consequence is that some issues arise which are irreconcilable, or at least not easily reconciled, and therefore it will take more time to resolve questions than has been the case with past issues handled by the UN Committee on the Peaceful Uses of Outer Space.

The fact that it takes more time to deal with sharply differentiated positions on issues, than is the case with those more amenable to negotiation and compromise, should not cause any loss of faith in the method of achieving agreement among nations by consensus, the method of work of the UN Committee on the Peaceful Uses of Outer Space and its subcommittees. This method has proved so successful in the past that it should serve as a model to other UN bodies, particularly those concerned with arms control and disarmament.¹³

3. There is constant interaction between national and international activities in remote sensing of the earth by satellites. We are handicapped in dealing with consequent problems because there are separate pools of experts with a tendency to work vertically within their disciplines rather than horizontally through multidisciplinary fields. Both specialists and generalists are needed, but they should be aware of all the factors that can affect the progress of their work. Scientists and engineers have a responsibility to inform the legal profession of those facts which are relevant to proposed systems of control and regulation. In fact, if they neglect to do this they are likely to be bound in the future by regulations which are unnecessarily hindering. Lawyers, economists and politicians should inform the scientists and engineers of the pressures in their fields of activity. Decisions are sometimes made on the basis of what is technologically feasible, the technology itself determining what can and what cannot be done. Scientists and engineers must take account of the fact that national and international laws can also prohibit or permit them to proceed with their work. There are many factors to be considered but often the scientific and technological community will look outside their expertise only to cost effectiveness or some other single economic factor.

4. There is need for more coordination between the Legal Subcommittee and the Scientific and Technical Subcommittee of the UN Committee on the Peaceful Uses of Outer Space. This need has been recognized but methods adequate to the task have not yet been developed. Recognition of the problem by UN members and staff gives hope for the future in providing for coordination.

5. It is very important that the United States not work out a plan for its own national operational remote sensing system without taking into consideration its impact on U.S. foreign

¹³ Galloway, Eilene. The Future of Space Law. A paper presented at the 19th colloquium on the law of outer space. Anaheim, California, October 1976. 11 p. This paper was given during the 27th Congress of the International Astronautical Federation.

relations as well as the effects of international factors on the U.S. program. This is an area not just of the role of the United States in the United Nations but also involves bilateral and multilateral agreements of NASA's international programs. Remote sensing of the earth by satellites is necessarily global, involving both governmental and nongovernmental entities, and we must think through the entire range of problems before taking action on pre-operational and operational systems.

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PROGRESS AND NEEDS IN AGRICULTURAL
RESEARCH, DEVELOPMENT, AND APPLICATIONS PROGRAMS

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ABSTRACT

The dynamic nature of agriculture requires repetitive resource assessments such as those from remote sensing. Until recently, the use of remote sensing in agriculture has been limited primarily to site specific investigations without large-scale evaluations. Examples of successful applications at various user levels are provided. This paper assesses the stage of development for applying remote sensing to many agricultural problems and suggests goals for planning future data characteristics for increased use in agriculture.

SDSU-RSI-77-06

Introduction

Agriculture as a dictionary definition is "the science or art of cultivating the soil, producing crops, and raising livestock". With such a simplistic definition, the term agriculture has grown to include an economically large sector of our society which is involved in production, marketing, researching, etc.--directly or indirectly--of agricultural products. Agriculture is sometimes viewed in the United States or other agriculturally developed countries as a method of balancing payments and we do not realize the basic necessity of AGRICULTURE AS FOOD until a shortage of certain commodities affects the marketplace in the cost or availability of certain food items which we feel are necessities for existence.

A recent review in Scientific American (September 1976: vol 235: No. 3) provided an excellent overview of the present world agriculture and agricultural production/population outlooks. Wortman (1976) illustrated the continued trend of increased production in surplus-producing countries including the United States, Canada, and Australia which provide food exports to the lesser agriculturally developed countries. He stated that to continue offering free or low-cost food to these governments is counterproductive to their long-term development. In addition, the sale of foodstuffs to many of the hungry peoples of the world can not be realized because most do not have monies or exchangeable commodities. Many of the countries have agricultural and water resources which could be developed but they lack the necessary information on their resources. Many have such limited resources that they have spatially developed to the fullest, and the major increases in production can only be derived by the application of new technologies such as genetically superior seeds or the use of chemical fertilizers. Therefore, within an agriculturally developed nation, the problems are well structured with each level of operation requiring different input; whereas, in a developing country, the need for information may be for only a central government for planning or implementing resource development.

Hopper (1976) illustrated the increased production realized from intensification of farming practices (Fig. 1). The use of remote sensing to provide required resource information to achieve technical innovation potentially will

benefit world food production. Resource awareness, a necessary first step in altering management practices to increase production, in many countries must be for educated public officials for implementing education programs for the farming population.

Why Remote Sensing in Agriculture

Agriculture contrasts with many resource disciplines because it varies with climate, economics, and many other external forces which determine what a farmer will plant and how the crop will grow. A single assessment of agriculture is not feasible to provide information because disaster, average, or over-abundant production has a certain probability of occurring every year.

Timely assessment of agricultural resources can reduce effects of insects, disease, and nutrient deficiencies on yield through efficient management practices.

A second aspect of agriculture is that in countries like the U.S., rapid transfer of information is available through the Cooperative Extension Service. The actual farming population is small and generally well educated in accepting the information with the capability to react where action could provide a benefit. Therefore, both the public and private sectors of agriculture have a suitable information system to accept and use information provided by remote sensing. In contrast, in regions of subsistence farming, 50-90% of the population may be agrarian living in rural areas with poor communication with population centers. These regions need information at higher levels of government. For many countries or states, agriculture is the largest economic commodity in their budget. Therefore, the impact of technological advances in agriculture can have a large effect on the growth and development of countries along with the stability of their peoples and governments.

The Structure of Agricultural Users

As with any segment of our society, an intricate network is established to serve the "grass roots" (farmers or producers). This network has developed in both the public and private sectors with each requiring different levels of information. Therefore, information on a global basis may alter price supports or import quotas which affect individual farmers. Management practices of individuals affect yield and influence total production which concerns managers at the global level.

The society of agriculture consists of a large group of private enterprises independently owned and operated. These private enterprises often combine to form cooperatives for purchasing, selling, or planning purposes. The enterprises are also represented by many county, state, or federal governmental bodies. Billingsley et al (1976) illustrated that the bulk of users who need information frequently can not accept highly sophisticated user products (Fig. 2). Unfortunately, present design characteristics of LANDSAT satellites require detailed digital processing to fully utilize data at "large" scales required by individual producers. Wiegand (1974) demonstrated that reflectance anomalies of chlorotic areas of a sorghum field which were visually apparent in larger-scale aircraft data were observed in digitally processed LANDSAT data. Until a mechanism is established to provide these detailed analyses on a routine and cost effective basis or until the scale of interpretation product is suitable for visual inspection of individual fields, use by the individual farmers will be limited.

In summary, agriculture is broad with information required at all levels and all types of agricultural systems. The following paper does not attempt to structure agriculture but has isolated a few problems at a few levels to illustrate present uses of remote-sensing techniques that vary with local situations. Much of the research in applying remote-sensing techniques is local

without testing over broad areas, peoples, and data-use structures. It is hoped that by demonstrating various successful uses of remote sensing, one's imagination will allow for visualizing possible applications for their specific problems. For purposes of this presentation, agriculture has been somewhat artificially categorized as global, international, national, state, regional, cooperative, and individual.

Example Users

A. Global - As outlined by MacDonald (1976), worldwide food production estimates are needed on a timely and accurate basis for those involved in the maintenance, operation, research, and development of food operation systems. The Large Area Crop Inventory Experiment (LACIE) was established as a cooperative project of USDA, NASA, and NOAA. During the phases II and III of the 3 1/2-year experiment, the capability of estimating area, yield, and production of wheat in the U.S. and other major wheat-producing regions of the world will be evaluated in the quasi-operational environment. The technology in analyses techniques required for such a large-scale activity can provide accelerated growth for many resource-application fields. After the two years of LACIE summarized by MacDonald (1976), he has concluded that "remote sensing supported by LANDSAT, together with the agro-meteorological approach to estimating yield, is capable of providing superior early season and at harvest estimates in major wheat producing regions of the world" and that "a significant improvement should be expected in the future". The effort required to develop procedures operational for global efforts is considerable. Whether or not the LACIE program can reach its accuracy goals, the technique development will be substantial for transfer to other problems which can have remote-sensing inputs.

Such problems as desertification can have immediate action. Presently, feasibility studies are being sponsored by the United Nations concerning the use of LANDSAT for monitoring desertification. Overgrazing, a cause of desertification, can potentially be assessed using LANDSAT (United Nations, 1977).

Resource problems with large areas which are dynamic can only be economically evaluated using satellite data. The present LANDSAT system offers an approach to obtaining repetitive, timely data which are not feasible to acquire by either ground surveys or aircraft flights over large, remote areas.

Problems of using only spectral data for interpretation in conducting crop inventories have been demonstrated by Draeger (1976). Comparative interpretations over large regions require all the available information including photographic patterns, textures, and tones along with ground knowledge. Therefore, we must repetitively compare suitable spectral and spatial information over large regions. That opportunity exists with satellite data.

B. International - Remote sensing can be important where information is required in an adjacent country or region. Extensive areas of Mexico are infested with the citrus blackfly. Hart et al (1973) found that medium to high concentrations of citrus blackfly fungus in tree tops were detectable using aerial color-infrared photography. Surveys must be conducted periodically to determine the potential of infestation in the United States. A procedure using aerial photography over ground surveys saved about \$44,000 (US) per year to inventory 56,400 hectares of citrus in Northeast Mexico. As resolution, both spectrally and spatially, allows additional applications in the assessment of diseases, insects, etc., the use of remote sensing can play an important role since ground surveys are normally quite difficult to conduct in adjacent countries.

C. National - Efforts to inventory regions on a national scope appear two sided. In developed countries, reconnaissance-level data are available. Therefore, the developed country will benefit from remote sensing by monitoring those dynamic features such as land use. Systematic approaches as

proposed by Anderson et al (1971) can be applied to maintain uniformity in the types and levels of information extracted. Many states have completed land-use inventories using remote-sensing approaches.

However, in developing countries, reconnaissance data generally are unavailable. For example, the 280-km Jonglei Canal is to be built in Southern Sudan to channelize approximately one third of the White Nile water which is normally lost in the SUDD region, a large swamp, due to evapotranspiration and groundwater seepage. Adequate resource data of the surrounding 160,000 km² do not exist to facilitate the development of the canal. Even though detailed ground investigations are required to locate and design the canal, locations of the closest sources of suitable aggregate, location of soils which could be irrigated, assessment of vegetation before project development, and measurements of drainage intensities and directions are not known at this time.

LANDSAT data offer the only reasonable interpretive data base at the required 1:500,000 scale for this large inaccessible region. Resource inventories conducted jointly by the Remote Sensing Institute in South Dakota, the National Academy of Science in Egypt, and resource scientists of SUDAN provided preliminary maps at a 1:500,000 scale with field verification after 18 months of project duration. High quality, tone-matched mosaics of interpretive imagery such as those in Fig. 3 are required. The mosaic prepared in both tone-matched color and black and white was an original scale of 1:500,000 covering the 160,000 km² with portions of only 12 LANDSAT scenes. Data from more than one season were viewed with various types of information extracted from each season. For example, in the dry season the frequency and size of burn patterns provide information relating to soil patterns. Drainage occurrence and density are more visible on wet season than on dry season imagery. The presence of surface water throughout the seasons can be mapped. Practical methods such as these photographic tone-matching procedures must be further developed to offer high-quality data to users at low cost.

D. State Level - Many states have applied LANDSAT data to land-use inventories. In most instances for a Level 1 land-use inventory LANDSAT provides the only economical source of data available on a state-wide basis.

Imagery can be used to provide a spatial awareness for disseminating information contained in line maps. For example, Westin (1973, 1974b) used LANDSAT data to provide information on conceptual dollar values of various regions in South Dakota and summaries of soil texture, soil slope, and soil test information. Many users do not understand soil variation mapped by a professional soil scientist but they can relate to the mapping units on the basis of pH or phosphorous level which may alter certain of their management procedures in the application of chemical soil additives. At the county level Westin (1974a) has provided a map of soil texture, organic matter content, and soil pH which is used to partially determine application rates of herbicides for weed control. The line map on a LANDSAT background at 1:250,000 scale can be used by applicators to locate actual fields within the region of interest. Barney et al (1977) prepared a user guide for Missouri agriculture in response to user demand. For example, the distribution of crops within a county is important to chemical and fertilizer salesmen in locating key dealers. Simple photographic interpretation of LANDSAT data provides this spatial information which can not be derived from the statistical data normally available. The simple interpretations can be accomplished (with a minimum of training) if suitable data products are available.

E. Regional - In vast areas of the western U.S., saline seeps are emerging through natural processes but the rate of formation is being accelerated by man through certain of his cultural practices such as fallowing land to build up soil moisture reserves. Miller and Bahls (1976) estimated that 57,000 hectares of land in Montana are not productive due to saline seeps and their growth is approximately 10% per year. Worcester and Brun (1977)

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estimated the growth of seeps in Western North Dakota was 700% to 1400% during the past 25 years. Horton (1977) summarized a joint Montana, North Dakota, and South Dakota project evaluating remote-sensing procedures for detecting pre-emergence, of saline seeps. Early indications are that the thermal spectral region in combination with aerial photographs (any film-filter) may provide an experienced soil scientist with considerable information in conducting the surveys. However, additional spectral regions such as microwave should be evaluated for a more direct measure of salinity and moisture levels. After the seep has formed, an alteration of management procedures has little or no effect on reclamation. However, with early detection of potential areas of seep formation, establishment of deep-rooted crops to reduce the level of the water table reduces the potential for seep development.

In agriculture, the important and economical uses of remote sensing are those which can provide base data to alter management decisions. In regional problems, even though the application may be used at the individual enterprise or farm level, the regional economic impact is large.

F. Cooperatives - Individual farmers normally do not have the scientific awareness or finances to apply remote-sensing procedures with our existing systems. Cooperatives can provide the mechanism for farmers to apply the technology. For example, in the sugar beet industry where the beets are harvested from fields and brought to a central storage facility to be processed, storage losses due to in-pile storage rot can be large. Moore et al (1975) found that predawn aerial thermography, for locating temperature anomalies associated with heat generated within the piles, could be used to isolate the spoiling areas. The spoiled beets are then removed from the piles to avoid further spoilage. With this early detection, a conservative estimate of savings for the sugar beet industry in The Red River Valley of North Dakota and Minnesota is \$1.75-million (US) dollars in an average year.

G. Individuals - One of the difficulties in assessing the use by individuals is the lack of documentation. Therefore, only a few examples from personal experiences can be illustrated. Moore and Rusche (1974) mapped the land flooded in 1974 in the Red River Valley of North Dakota. In 1977, a farmer requested an aerial photograph which documented the percent of flooded land on a farm he was contemplating purchasing to determine if he wished to pursue the transaction. Since land prices had advanced into the hundreds and thousands of dollars per hectare, the individual was considering a considerable financial sum and needed all available information on which to base his decision. In another case, a farmer in Kansas had an irrigated field with a serious infestation of weeds. Although he knew of the presence of the weeds, he could not determine on the ground their spatial extent within the field. In his effort to optimize return on his investment, he needed to decide whether to cut the field early for silage or to allow the crop to mature for grain. On color-infrared aircraft photography available because of an on-going drainage study, the spatial extent of weed infestation was easily interpretable. Because 40% of the field was infested in mid-August, the farmer harvested the field for silage. Many of these uses would exist if timely, high quality data were readily available.

Summary and Recommendations

Remote sensing does have application in agriculture. Agriculture is dynamic and has the economic need for timely data for management decisions. Perhaps the greatest deterrent to use is presently a combination of effects of data scale from satellites and timeliness of data availability. These problems can be overcome and in a slow evolutionary process their use will increase. Billingsley et al (1976) provided a summary of the "state-of-the-art" in agricultural applications presented in Table I. Most applications require further research and development before they can be considered operational for any region. Most procedures have been developed and evaluated over limited

geographic areas.

TABLE I. State of the art of remote sensing in agricultural applications.

Application	State of the Art		Users*
	Operational	Development Research	
High Water Tables	X - - - - X		CA, CSD, DD, F, FA, ID, SCS, USBR, BIA
Salinity	X - - - - X		CA, CSD, DD, F, FA, ID, SCS, USBR, BIA
Irrigation Management	X - - - - X		CA, CSD, F, FA, ID, SCS, USBR
Soil Moisture	X - - - - X		CA, CSD, F, FA, ID, BIA
Water Budget	X - - - - X		BIA, CSD, FA, ID, SA, SCS, USBR
Ground Water Development	X - - - - X		CSD, F, ID, SCS, SG, USGS, BIA
Soil Survey--Reconnaissance	X		CA, CS, F, FA, SA, SCS, USBR, BIA
Seed Germination Requirements		X - - - - X	CA, F, ID, SA
Crop Surveys--Acreage	X - - - - X		CA, F, FA, SA, SRS, BIA
Crop Surveys Yield		X - - - - X	CA, F, FA, SA, SRS, BIA
Range Surveys--Biomass	X - - - - X		CA, F, FA, SA, BIA
Disease and Insects	X - - - - X		CA, F, FA, SA, SRS, USBR, BIA
Land Erosion Potential	X - - - - X		CA, CSD, F, FA, SA, SCS, USBR, BIA
Weed Infestations		X - - - - X	CA, F, SA, BIA
Fertility Needs		X - - - - X	CA, F, FA, SA, SCS, SRS, USBR, BIA

*BIA-U.S. Bureau of Indian Affairs
CA-County Agents
CSD-Conservancy Subdistricts
DD-Drainage Districts
F-Farmers

FA-Other Federal Agencies
ID-Irrigation Districts
SA-State Departments of Agriculture
SCS-Soil Conservation Service

SG-State Geologists
SRS-Statistical Reporting Service
USBR-U.S. Bureau of Reclamation
USGS-U.S. Geological Survey

(after Billingsley et al, 1976)

Recommendations to increase the numbers of users involved in U.S. agriculture are:

- establish more information dissemination centers
- tailor products in scale and thematic information
- improve spatial resolution of satellite data
- include thermal and microwave sensors on satellites
- more timely data delivery
- increase product visibility

- establish aircraft programs with rapid data delivery
- greater USDA involvement
 - knowledge of user products
 - available extension service
- increase both basic and applied research within well-defined framework plan
- more frequent coverage during the growing season
- include cloud-penetrating sensors
- improve signal/noise

The foreign concern is to assure that high quality data over remote regions are easily available at a nominal cost.

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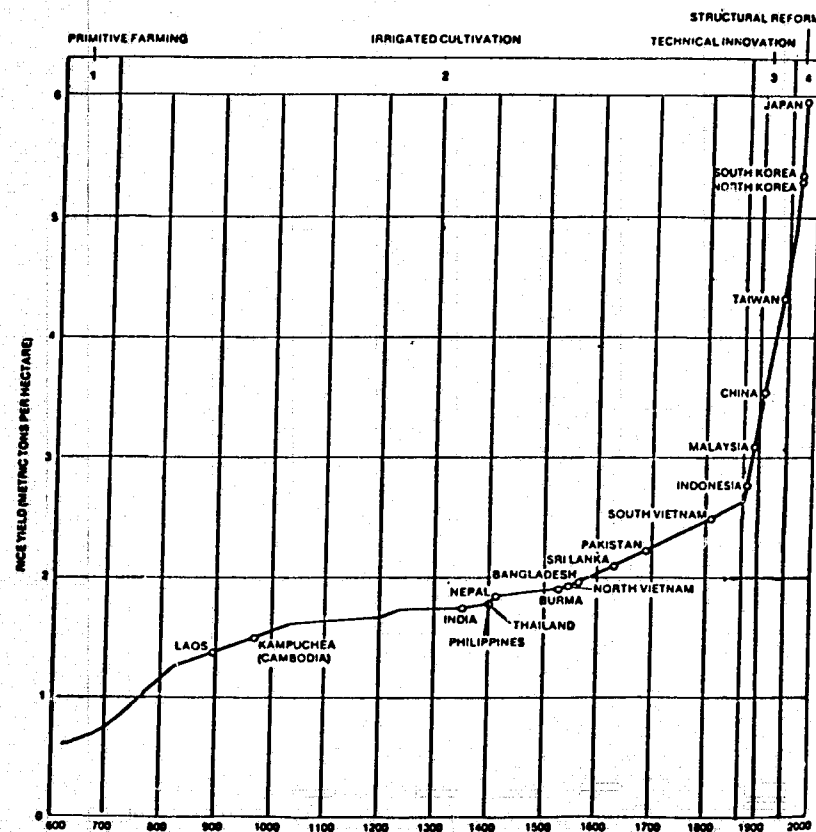


Fig. 1 - The effect of technical innovation and intensification of farming practices on the yield of rice. (After Hopper, 1976).

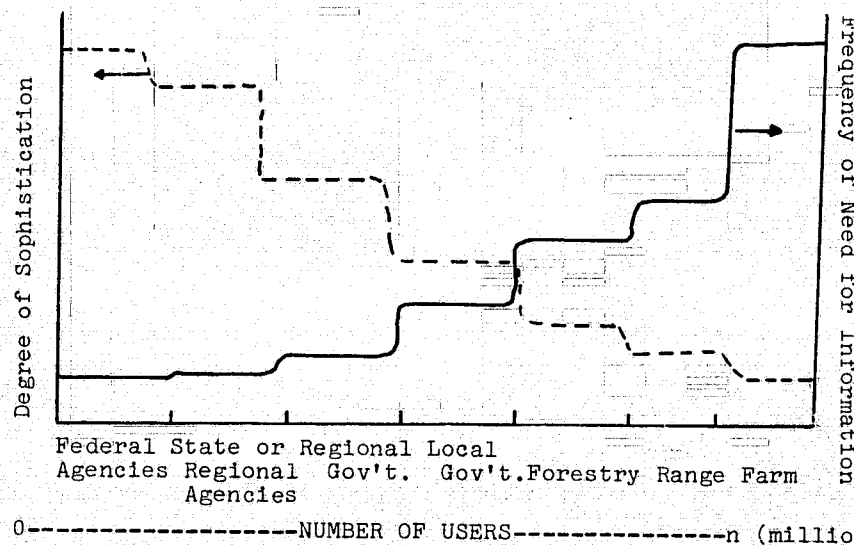


Fig. 2 - The need and level of information required for various agricultural users of remote-sensing technology. (After Billingsley et al, 1976).

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Fig. 3 - A tone-matched black and white mosaic of MSS-7 LANDSAT data as a data base covering 160,000 km² of the SUDD region of Southern SUDAN. Portions of 12 scenes are required for this 1:3,000,000 scale mosaic (original working scale was 1:500,000). Tone matching of these photo-interpretive products allows the resource scientist to view the total area with detailed data which appear as one scene.

REMOTE SENSING AND TODAY'S FORESTRY ISSUES

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ABSTRACT

The purpose of this paper is to examine the actual and the desirable roles of remote sensing in dealing with current forestry issues, such as national forest policy, supply and demand for forest products and competing demands for forest land.

A most critical problem in forestry is the developing shortage of wood. Productivity must be increased, more intensive management must be introduced, and current supply must be accurately estimated. Significant uses for both satellite and airborne data have developed in forest management and broad regional planning. However, the shortage of wood has emphasized the weakness of existing forest inventories and has increased the importance of those projects which lead to more detailed information on forests coming under intensive management. Projects involving multistage sampling, linking information flowing from aerial photography and ground sources are now particularly relevant, as are the developments in low altitude aerial photography. Since a high percentage of the cost of wood is incurred in harvesting and transportation, remote sensing should pay increasing attention to terrain assessment, trafficability and other information required in planning harvesting operations and transportation networks. Special problems have to be solved in the inventory and management of resources in developing countries.

The developing supply crisis will put pressure on reforestation programs, and on the rehabilitation of naturally degraded or mismanaged lands. At the moment, the most promising approaches to the assessment of planting sites and reforestation success are through adaptations of traditional photogrammetry and photo interpretation; advances will have to be made.

Forest protection continues as a critical area deserving more attention. Satellite data have proved valuable in assessing forest fuels and fire damage and thermal imagery has contributed in fire detection, mapping and suppression. However, the practical advances in the appraisal of insect damage from thermal imagery and satellites have been less spectacular and particularly in the assessment of the spruce budworm damage, major problems remain.

Wood is also being considered as an additional source of energy and interest is increasing in producing fuels from wood. These approaches have posed the new problems of estimating total biomass and transportation costs for new products. The estimates required are those which are directly relevant for industrial developments; the purely scientific approach is less desirable.

Other forestry issues involve concerns for the quality of life, conservation and environmental protection. Here remote sensing has served well in the completion of integrated resource inventories of parks and conservation areas and in thematic mapping. It has also been employed in urban forestry, in assessing the problems and potential of trees in cities and it plays a special role

in environmental assessments preceding large capital projects, such as dams, pipelines and transportation corridors. Satellite imagery has a promising role in large national and global monitoring programs which emphasize both the monitoring of resources and environmental matters.

INTRODUCTION

Important changes are taking place in forestry and the relevance of remote sensing programs to current problems should be questioned. Are the advances being made in the areas that matter? Are shortfalls in essential capability developing? The answer to these questions does not require an appraisal of the scientific merits of new research nor does it demand a detailed account of the success in transferring the results of research to practical application. We must, however, understand the broad outlines of developing forest policy, of economic trends in supply and demand, of demands for environmental standards and of specific problems related to energy or threats to the forest resource.

WOOD SHORTAGE AND THE NEED FOR MANAGEMENT

One of the first observations is that world demand for wood will increase as population and aspirations rise. However, there are severe limits on supply: Western Europe is a wood-deficit area and the Soviet Union will not be an important source of wood exports. Its resources have been greatly overestimated (Steenberg 1976, Sutton 1975). In the United States the outlook for meeting domestic demand and current export levels is more optimistic. To some extent this is the result of increased interest in forest management which has found expression in the National Forest Management Act of 1976. This Act establishes guidelines for the maintenance of forest cover, for sustained yield management and the identification of lands not suited for timber production, for land rehabilitation and reforestation; it sets high standards of long range planning, maintenance of forest cover and silviculture for lands under the National Forest System.

In Canada the forest policies in practically every province are under review and we are probably seeing the political realization that the days of exploitation with some regulation are over and must be replaced by intensive forest management. We know of sharply rising costs, of large losses to insects and fire and of extensive areas of unsatisfactorily stocked lands; but the national picture is blurred by inadequate information on forest inventory and productivity.

In the developing countries, many of which are in the tropics, the emphasis remains on the exploitation of existing resources through logging ventures or the establishment of industry. However, tropical woods are no substitute for conifers and therefore the coniferous forests of the temperate zones will continue to play an essential role in meeting the world's demand for forest products such as pulp and paper and construction material.

In the tropics far less is known about the assessment of timber volume, trafficability and logging costs; enterprises have failed for lack of such information. We simply do not have much experience in applying remote sensing and aerial photography in tropical forestry, and sensor development and interpretation research have concentrated on the northern forests, with their much simpler species composition. In the tropics one must also be prepared to deal with major changes in land use which often have undesirable effects - forests are removed to make room for transportation networks, mining developments, or for agriculture and colonization. Such changes in land use must be observed and brought to the attention of policy makers and the general public; global and national monitoring networks are required.

The often predicted large increases in the use of tropical hardwoods have not materialized, but we see in the tropics and subtropics a trend towards the establishment of large coniferous plantations - the big projects in Brazil and Chile are examples. Such projects reinforce the need for sustained yield management, for monitoring plantation success and for protection against fire, insects and disease outbreaks which have much greater impact in large monocultures.

REGIONAL INVENTORIES

The problems of tightening supply raise the requirement for good inventory information on a regional basis. Such information is usually presented as thematic maps or as statistical data. Remote sensing, particularly with the addition of data from Landsat and Skylab, has made major advances in providing such information. We have many reports documenting the success of space programs in land use mapping, particularly when satellite data are used in conjunction with aerial photography. The importance of such maps varies from country to country. I suspect that in the United States and Canada, where important management decisions tend to be made locally, their importance is often exaggerated by professional planners.

LANDSAT FOR INVENTORIES IN THE TROPICS

The broad classifications promised by Landsat are of special importance in those areas of the world where little inventory information exists. The large recent inventories of Brazil, where radar imagery was combined with aerial photography and Landsat (Fagundes and Pinto, 1976) were carried out in such a situation. Landsat also has a vital role in the current national resource inventory of Indonesia, described by Darmoyuwono and Hadisumarno (1976): photo maps at a scale of 1:250,000, prepared from Bands 6 and 7 of Landsat, are used as base maps for areas without adequate topographic maps. On these new maps, which are essentially enlarged Landsat images, the geographic grid, geographic names, and symbols were imposed. Roads were enhanced or, if they could not be seen, were drawn from existing data. Darmoyuwono and Hadisumarno (1976) make special reference to the mapping of changes in the extent of nonforested areas and the identification of river patterns, shorelines, logged areas and changes in river banks and sandbars.

Over recent attempts to map land use in largely forested terrain in the tropics have recently been completed using Landsat. One of these is a map of a portion of Peru by the Oficina Nacional de Evaluacion de Recursos Naturales (1975). This map shows broad zones combining physiography and forestry. The forest classes mapped include riparian forest, forest on high terraces and mountain forest. A vegetation map of Bolivia has also been completed.

Another study by Bruneau and La Toan (1976) is an attempt to map forest and agricultural lands in a portion of northern Thailand using both black and white Landsat imagery and colour composites. The region described has, in contrast to the area in Peru previously mentioned, a long history of settlement. The authors, whose method was traditional interpretation, emphasize that success depended on a thorough knowledge of the area and on experience with aerial photographs.

One interesting development, with trial applications in Indonesia, has been the combination of radar and Landsat imagery. Side-looking radar imagery emphasizes topographic relief, but Landsat allows the classification of vegetation and provides information on areas in radar shadows. The U.S. Geological Survey and Goodyear Aerospace Corporation have investigated the development of composite images combining side-looking radar and Landsat. The results are an interesting combination with topographic features provided by radar imagery and thematic information from Landsat (Harris and Graham, 1976).

LANDSAT FOR INVENTORIES IN TEMPERATE ZONES

Experiments involving Landsat have been most numerous in the temperate regions. In an attempt to draw general conclusions let us for the moment speak in terms of a classification system developed by Anderson, Hardy and Roach (1972) in which a forestry "Level I" classification means the separation of forest land from nonforest land and Level II implies identification of hardwoods, coniferous and mixed forest. Landsat is a good Level I classifier; a number of articles, in particular Aldrich, Norick and Greentree (1975) and Heller's summary (1975) of U.S. Forest Service experiments, support this.

However, to complete a forest inventory one must map at least at Level II. Experiments by Aldrich, Norick and Greentree report poor estimates of areas by Level II classes which, in their case, meant separating pine from hardwood. They make an interesting observation that the first impression during a visual comparison of a thematic map prepared by computer was good. However, subsequent statistical analysis showed the deficiencies at Level II. The human eye and brain were incapable of analyzing all the data at a glance and only objective tests revealed the truth.

However, there are detailed analyses of classification errors which show that digital analysis of *multidate* imagery can lead to classification accuracies in excess of 80%. The work by Kalensky and Scherk (1975) which, incidentally, also involved separation of pine and hardwoods, is one example. High accuracies can only be achieved with detailed ground calibration data and by combining Landsat data from more than one season for reliable separation of deciduous and evergreen stands. An evaluation of Landsat is not complete until multidate imagery has been considered. Major difficulties, however, will remain as we attempt to extrapolate results from one test site to larger regions.

Results of universal significance will have to rely on basic research and evaluations of existing systems. Tucker and Maxwell (1976) have contributed in this field through a comparison of the effectiveness of several band widths for the monitoring of grass canopies. Their approach was to numerically integrate various band widths to approximate other bands and to correlate reflectance with total biomass, total chlorophyll, and leaf water content. They confirm the known redundancy between Band 6 and 7 of Landsat and recommend that the absorption (.69 to .70 μm) and the transitional zones (.70 to .74 μm) be avoided and that, for example, Band 3 or RBV be shifted to .75 - .87 μm , the region of enhanced spectral reflectance.

SKYLAB

Far less has been reported about success with Skylab; this is understandable because Skylab was not a long term space program and did not provide the extensive coverage of Landsat. Nevertheless, there is evidence that interpretation of forests using Skylab photography may allow more detailed classification than

Landsat imagery, although forestry results to date have not proved this. The comprehensive evaluations of the U.S. Forest Service (Aldrich, 1976; Aldrich, Roberts, Greentree, Norick and Waite, 1976; Weber, 1976) which relied on the conventional photo interpretation approach and enlarged Skylab photographs revealed important limitations: forest types were correctly identified only 50% of the time; upland and bottomland hardwoods could not be separated except in the most obvious cases; pine and hardwood could not be distinguished from mixed pine-hardwood; the longest dimension of insect infestations had to be over 85 feet to be detected.

Skylab results outside forestry have been promising and there obviously are applications in cartography and topographic mapping. For example, Lins (1976) reports classifications at Level III for urban land use. At this level such categories as "single family residence" and "multifamily residence" are separated. Interpretation accuracy was 83%, with the quotient of points-the-same over total points used as a measure of accuracy.

EVALUATION OF ACCURACY

One severe limitation to the acceptance of new remote sensing techniques is that one cannot readily compare accuracies reported by different investigators. To illustrate this difficulty consider Table I, a hypothetical set of results. It is the familiar "Confusion Matrix" which in the early years of remote sensing was extensively used by the Forestry Remote Sensing Laboratory in Berkeley.

TABLE I. CONFUSION MATRIX. (Hypothetical interpretation results)

Classification	Correct classification ("ground truth") Total number of points or pixels	Interpreted as		
		Pine	Hardwood	Other
pine	40	28	8	4
hardwood	60	15	42	3
other	100	6	14	80
	200	49	64	87

Now think of the plight of the potential user who would like to compare the results of two leading experiments, Aldrich *et al.* (1975) and Kalensky *et al.* (1975). The pattern of Aldrich would be to cite "point accuracy" for pine = $28/40 = 70\%$ and an "area accuracy" based on a comparison of 40 and 49. Kalensky would speak of an "overall classification accuracy" for the whole scene of $(28 + 42 + 80)/200 = 75\%$, which considers both error of omission and commission. For pine it would be $28/(28 + 8 + 4 + 15 + 6) = 45.6\%$.

Other measures of accuracy have been advocated: e.g., Hord and Broome (1976) recommend a single value which combines errors in classification, line placement and control point placement. All these measures are logical, but until there is some standardization the user will be confused. As an interim remedy all investigators should be urged to include the complete "Confusion Matrix" in their results. It is somewhat awkward, but the most common measures of accuracy can be calculated from the data given. In the long run some further conventions will have to be agreed to by the scientific community or they will be laid down with the heavy hands of funding agencies.

LARGE-SCALE PHOTOGRAPHY

Most investigators have concluded that a promising role for satellite remote sensing in forest inventory is through multistage sampling. A satisfactory contribution at the first stage requires at least classification capability at Level II. If this should be accomplished, then we have to deal with the other stages which are best completed by aerial photography and ground work. In this area, I regard as highly relevant the work in large-scale aerial photography carried out in both temperate and tropical regions (Edwards, 1972; Nielsen, 1974; Nielsen and Aldred, 1976; Aldred, 1976; Rhody, 1977). The systems involved are now operational for northern forests and have been tested in the tropics - in Guatemala, Surinam, and most recently in Costa Rica. Low altitude photography provides detailed information required for intensive management. It is promising not only because it costs less than methods relying heavily on ground survey, but also because in recent years it has become increasingly difficult to persuade skilled persons to work in the woods, even at attractive salaries.

INFORMATION FLOW

There is another task for the remote sensing community if it is to prove its usefulness in forest inventory: the information flow in current forest inventory systems has to be understood. If we develop technically successful methods that do not fit into existing systems, and if we cannot replace the existing systems with new ones, then we are wasting time. There is a real problem in the application of satellite data. Most forest inventory systems acquire data at local levels and then complete regional and national inventories by aggregation of local data. Bickerstaff (1975) has described the system in Canada, which is of this nature and has much in common with the patterns in other countries.

Satellite information is most suitable where information is gathered by going from the general to the particular. Technically, the temptation is to develop systems where the information flow is from the top down – the reverse from the usual forest inventory. This has to be understood and suitable compromises have to be worked out before the advances in remote sensing can adequately contribute to the assessment of our forest resources.

SUPPORT OF INTENSIVE FOREST MANAGEMENT

The discussion of forest inventory has been extensive not only because this is a highly relevant area, but also because it is a traditional field for remote sensing and one which has received much attention in the past. A neglected area, which is equally relevant, is the development of remote sensing techniques useful in the detailed and intensive management of the forests. It involves the monitoring of the effects of silvicultural practices, the evaluation of success of reforestation, regeneration surveys, and the identification of mineral deficiencies in soil. To support intensive management, remote sensing should also provide information on stand density by comparing actual densities with desirable norms; it should estimate trafficability before deployment of harvesting machines, it should provide efficient methods of mapping logged areas, even if only partial cutting is involved, and it ought to provide techniques for estimation of growth rates. For each of the problems mentioned, some efforts can be cited; most readily recalled are published and unpublished attempts at assessing trafficability and regeneration. However, the entire area has not been systematically approached, yet it will become increasingly important. Aerial photography and sensors on low flying aircraft will play the main roles.

FOREST PROTECTION

Concern with present and future sources of supply inevitably leaves us with urgent problems of protecting forests from damage, in particular from insect infestations and fire.

Technically the application of remote sensing in insect damage appraisal is difficult. With Landsat in particular, the results to date have often not justified the optimism expressed in the past. For example, in spruce budworm damage surveys, large areas of complete mortality can be outlined, but little new can be reported about the mapping of damage levels. The most valuable work in budworm damage assessment has proved to be in aerial photo interpretation where numerous publications are cited by Murtha (1976). Specific reference is made to the carefully documented study of Ashley, Rea and Wright (1976) which again shows that there are no quick solutions to assessing damage. Past efforts to assess budworm damage have encountered problems of uncertainties of ground information, low contrast between damaged and healthy areas, and complications introduced by presence of underbrush and deciduous trees. Ashley reminds us of how careful one has to be in the definition of objectives. The correct photo specifications may be quite different if the desire is to map defoliation, mortality, or overall condition after several years of infestation. Also success in interpretation requires a good understanding of the target and its surroundings. For example, a heavy cone crop or the fact that clipped needles are held in the webbing of the insect significantly affect appearances on photographs and have to be considered.

The need for a cautious approach in advocating Landsat as a tool for monitoring stress in vegetation is supported by experiments in the Black Hills National Forest (Weber, Roberts and Waite, 1975). Here the investigators showed considerable success in classifying major land use categories, but failed to obtain cover type acreage estimates and information on damage (mountain pine beetle) that was sufficiently precise to be useful to the forest manager. Their methods included visual interpretation of imagery as well as computer-assisted mapping relying on the LARS and PSW systems. However, undeniably, they say the synoptic view of the entire Black Hills produced something of value otherwise unavailable to land planners and forest managers.

For detection of stress in trees in urban environments, one should pay attention to research at the College of Environmental Science and Forestry at Syracuse, N.Y. Two recent reports (Lillesand, Brock, Roberts and Johnson, 1975 and Eav, Lillesand and Manion, 1977) describe how close range photography and colour infrared aerial photographs (1:6000) were analyzed to show the response of foliage to stress. Narrow band filtration and ratioing of data from film layer records were employed to allow for the degrading effects of haze, atmospheric attenuation, lens flare and film processing. The condition and environments of about 3,000 trees were correlated with the film exposure in the green, red and infrared bands of colour infrared film. Measures for estimating stress on the ground and by aerial photography have been developed; research

continues with emphasis on procedures for predicting stress.

The emphasis in damage surveys will have to shift to the identification of situations where remedial action can be taken. Here one should refer to the interesting approach recently taken by Heller and Miller (1976) in Idaho. An attempt was made to identify stands of fir which were susceptible to attacks by a destructive defoliator, the Douglas-fir tussock moth (*Orgyia pseudotsugata* McD.). Colour infrared photography (1:4000) of the Blue Mountains of Oregon and Washington was employed. The analysis of hundreds of sample plots revealed that stands with high probability of defoliation were at lower elevations, on eastern or southeastern exposures, on or near ridge tops, open grown, multistoried or of high density. The authors draw conclusions about the degree to which presence of any of these characteristics influences the probability of defoliation. Such research appears particularly relevant under the current trend towards intensive forest management, which requires the prevention or control of insect outbreaks. This is an objective which goes beyond the traditional question: "How extensive is the damage and where is it located?".

We will have to be more selective in our choice of problems and will have to concentrate on the major pests such as the spruce budworm which is currently the most destructive. Also we should single out those situations where useful action can be taken, if problems are identified. We should perhaps devote less attention to the purely systematic approach to damage identification and to the estimation of damage in non-economic terms.

In fire protection one of the important contributions will be in fuel-type mapping, that is in the mapping of groups of stands with uniform fire behaviour characteristics. Such information is required for proper management planning and for allowing fast decisions on the method of attacking fires. Fuel-type mapping includes the mapping of recent burns, cutovers and cover types, and the problem approaches the tasks set by forest inventory requirements. Digital interpretation of Landsat data offers distinct possibilities and recent advances are described at this symposium (Kourtz, 1977).

Another area of great importance is the application of scanners during fire control to guide fire suppression efforts. This application together with fuel-type mapping are the most important applications and appear more rewarding than further developments in fire detection.

ENERGY

Another task for remote sensing in forestry follows from the current and projected shortages in energy, in particular in liquid fuels. In the past, the traditional answer to this problem has been to expand the production of coal, oil and gas and nuclear power. This approach has become increasingly unattractive as many, including Lovins (1976) have so convincingly argued. Costs are too high and capital markets are disrupted by the tremendous investments required; the environmental penalties of large capital projects are often unacceptable and social results involve such unpleasant consequences as major centralization of management and a world of subsidies, regulations and state intervention. These arguments have been noted by governments and interest is growing in alternate solutions of the energy problem, which involve conservation and the use of renewable resources. The use of biomass, including forest biomass, will play a large role. Certainly the potential is there: data presented by Earl (1975, p. 43) show that only 13% of the world's forest increment is harvested. Fifty-one percent of the world's increment is in the tropics, and there only 11% is harvested. In 1970 over 90% of the world's energy consumption derives from nonrenewable fuels. Yet the maximum possible energy production from available wood and charcoal is slightly larger than total world energy consumption in 1970! (Earl, 1975, p. 19-21).

For the remote sensing community the broad outlines of the task to be met have appeared. It will be necessary to support national planning and policy development and macro-economic studies. These require assessments of supply, climate and soil as well as estimates of biomass production under various management alternatives and predictions of harvesting and transportation costs. A good indication of problems and possible initiatives can be found in the Proceedings of the recent Energy Research and Development Conference held in Reston, Virginia, this February, under the sponsorship of the Energy Research and Development Administration; potential sources of biomass, possible production, management alternatives, technical feasibility and costs were considered.

Remote sensing will be called upon to produce reliable estimates of available biomass. Some, but not enough, such studies have been made in forestry; they appear to be more common in agriculture. As an interesting remote sensing application note the recent work by Pearson, Tucker and Miller (1976) in which airborne MSS imagery was combined with data from hand-held cameras to provide estimates of grass cover biomass. In forestry the problem is more complicated than in grasslands; studies will have to go far beyond the estimation of surface chlorophyll. The challenge is to combine modern remote sensing techniques, and in this case radar and profiling lasers must be included, with the traditional photogrammetric approaches to inventory, (e.g., stand volume tables) and with the mass of scientific data on weight and fibre content of individual trees and shrubs.

MONITORING

The requirements for remote sensing to contribute in forest inventories and to support intensive forest management, protection and the search for energy, stress established forestry goals. These are often close to environmental objectives. For instance, the mandatory studies of environmental impact of capital projects can no longer be separated from resource development. The methods, too, are often similar: the forest and vegetation maps which served the environmental assessment preceding the development of the northern transportation corridors were not so different from those that would have been required had the objective been a purely engineering study. True, there were some changes, such as more emphasis on rare species, on vegetation as a wildlife habitat and on the identification of unique or sensitive conditions, but the main requirements remained a clear and objective description of the land and vegetation.

A new area of global environmental monitoring has emerged, which for forestry will mean participation in such endeavours as the tropical forest monitoring project developed by FAO under the leadership of Professor F. Loetsch*, (Baltaxe and Lanly, 1976). This program, now in the pilot trial stages will tell us of shifts in forest conditions and land use in the tropics. It is one of several international monitoring schemes. National programs are also under consideration, for example, in Canada; concepts are discussed by Sayn-Wittgenstein and Aldred (1976). These programs are legitimate priorities because there can no longer be any argument about the necessity to make systematic observations of the forest environment, both to receive early warning of developing problems and to understand the systems involved. Large, efficient forest monitoring schemes must rely on permanent sample observations; in their development one can thus draw upon long experience with permanent sample plots used for maintenance of inventories. Technically the global schemes are exciting because they allow observations which were impossible before the days of satellite remote sensing. This brings the added benefit of minimal resistance by users: the systems are entirely new; they do not replace existing systems and users do not have to pay the price of abandoning entrenched procedures.

CONCLUSIONS

In recent years the remote sensing community has enjoyed an opportunity to engage in a broad range of scientific experiments involving new techniques, in particular in the analysis of Landsat data. During this period we often spoke about the need to concentrate on areas where benefit cost ratios are high and payoffs are visible, but much effort has gone into satisfying the curiosities of individual scientists or into testing ideas removed from practical problems. This is a normal and desirable part of research. These experiments have left us with a good understanding of what is possible with remote sensing and with Landsat in particular. The current state of the art in remote sensing has been well reviewed in a number of recent publications, including Fischer, Hemphill and Kover (1976), Fontanel (1976), Otterman, Lowman and Salomonson (1976), and for damage assessment, Murtha (1976). With reference to Landsat, I have, in Table 2, updated earlier estimates (Sayn-Wittgenstein and Wightman, 1975) of the state of Landsat applications, as seen by a number of scientists in the Canadian Forestry Service.

Clearly, we have reached a period of some levelling off in expectations and of consolidation of results. This is the time to concentrate efforts on the most critical issues in forestry. Most of these evolve from the fact that future demand for wood products will exceed the supply of economically accessible wood and from increased competition for the use of forest land. Increasing needs for accurate information on supply will follow, accompanied by requirements to protect resources and to support silvicultural operations and more intensive management. Furthermore, there is an indisputable requirement for global monitoring systems for both economic and environmental reasons.

The following tasks emerge as high priorities:

1. Improve forest inventory information at global, national and regional levels.

A sound immediate objective would be to advance the state of the art to the point where resource satellite data can be consistently used to provide reliable land classification at Level II of Anderson's scale. This will require far more emphasis on multistage analysis and use of data with high position accuracy. Success in forestry will mean that coniferous forests, deciduous forests and mixedwood forests can be distinguished over a broad range of forest conditions. It is not good enough to show that it can be done in a few test areas after extensive trials. If more than Level II information can be obtained, so much the better, but this objective is a minimum goal which is probably feasible, but has not yet been reached.

2. More emphasis should be given to remote sensing methods which support intensive forest management at the local level, where the most important decisions are made. This implies further development of multistage sampling designs, the testing of survey methods employing large-scale

*Formulation of a Tropical Forest Monitoring Project Report, Food and Agriculture Organization of the United Nations. Rome, 1976.

TABLE 2. STATUS OF CANADIAN FORESTRY SERVICE LANDSAT APPLICATIONS.

Problem Area	Status as estimated in			Likelihood of Success as estimated in		
	March 74	Sept 75	March 77	March 74	Sept 75	March 77
1. Broad cover type mapping	R	D-0 ↑	D↑	H	H	H
2. Arctic vegetation mapping	R	R	R	M	H ↑	M ↑
3. Land classification, drainage	D	D-0 ↑	D↑	H	H	M ↑
4. Timber volume estimation (multistage sample)	R	R	R	H	H	M ↑
5. Revegetation on burns and cutovers	R	R	R-D ↑	H	H	H
6. Fuel-type mapping	R	0 ↑	D↑	H	H	H
7. Phenological monitoring	R	R	R	M	M	M
8. Snow melt patterns	R	R	R	L	L	L
9. Mapping clearcuts	D	D-0 ↑	D-0	H	H	H
10. Monitoring of other human activity (roads, seismic lines, hydro lines)	R	R	R	M	M	M
11. Mapping recent burns	D	0 ↑	0	(in most cases)		
12. Damage (non-fire) large severe kills	R	D-0 ↑	D↑	M	H ↑	M ↑
13. Damage - other defoliation	R	R	R	L	M ↑	L ↑
14. Land slides	R	R	R	L	L	L
15. Mapping flooded areas	0	0	0	H	H	H

Status: R research, D - ready for demonstration, 0 operational.
Arrows indicate upward or downward revision from previous entry.

photography and the evaluation of profiling lasers. Remote sensing also has to pay much more attention to the monitoring of the successes of silvicultural activities, particularly of those involving reforestation, land rehabilitation and improvement.

3. In forest protection the need is to concentrate far more selectively on the major insect pests and on situations where something can be done about problems that are identified. There should be less attention paid to damage assessments in purely scientific or biological terms and more to economics. In forest fire protection the priorities are fuel-type mapping and fire mapping.
4. Forestry should participate actively in national and global environmental monitoring schemes. Such schemes require inventory information as a baseline for the measurement of changes and also as a basis for understanding the significance of these changes. Therefore we should try to ensure that these schemes are compatible with forest inventory data. This means common definitions, common data grids and, wherever justified, collection of common information. Ideally we could then arrive at systems which link forest resource inventories with monitoring systems somewhat as the more advanced forest inventories link temporary and permanent sample plots.
5. An immediate opportunity exists to contribute usefully to the solution of energy problems. In forestry, remote sensing has two tasks: one is to improve the current approaches to the estimation of biomass and the other to support macro-economic studies of wood and biomass production under

various management policies.

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REMOTE SENSING IN RANGELAND MANAGEMENT:
AN OVERVIEW OF APPLICATIONS AND BENEFITS

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SUMMARY

Remote sensing has been available to range managers since the late 1930's to assist in mapping and preparing inventories of the range resources. Initially, only black and white aerial photographs were available, but subsequently color, color infrared, multispectral, and multistage photography and imagery have become available. This paper reviews the users and uses of remote sensing in range management and assesses its benefits and future uses.

Initial acceptance and utilization of aerial photographs were hindered by the relatively high cost of acquisition and interpretation relative to conventional ground techniques and the low value associated with the forage resource. However, recent multiple-use land management legislation and the relatively high cost of conventional ground based inventory techniques have caused range managers to more fully use remotely sensed data.

In the past few years federal land management agencies in the United States have been directed to acquire detailed resource information to support relatively intensive management activities and assess impacts associated with grazing, strip mining and development of facilities. As a result agencies such as the Bureau of Land Management, Fish and Wildlife Service, and the Forest Service are using color and color infrared aerial photographs to inventory, assess and monitor range resources. For example, the Bureau of Land Management has recently completed a surface inventory of 15,000 square miles in southeastern Montana and western North Dakota using color infrared photographs at a scale of 1:40,000 and 1:80,000.

In other regions of the world where range management practices are less intensive, management agencies are using Landsat imagery in conjunction with aerial photographs to prepare baseline inventories. Utilization of Landsat imagery by the Agency for International Development, United Nations Development Program, the United Nations Food and Agriculture Organization, and private remote sensing consulting firms demonstrates a trend of increasing acceptance of Landsat based data. For example, a recent range inventory in Iran incorporated the analysis of Landsat and aircraft data with ground sampling to estimate rangeland productivity.

Automated analysis and classification techniques using Landsat data have developed rapidly, and offer much promise for rangeland management. These techniques are particularly useful for making national or regional rangeland inventories and for preparing vegetation maps where baseline resource data are inadequate or nonexistent. In Alaska detailed maps of vegetation cover do not exist; consequently, the Bureau of Land Management is testing the use of computer-aided analysis techniques using Landsat data to prepare more accurate vegetation maps. The extent to which these techniques are utilized in rangeland management may be governed by a) the requirement to produce resource maps at a level of detail which cannot be derived from Landsat data, b) the availability and cost of analytical equipment and/or services, and c) the availability of trained personnel to use these techniques or evaluate the results of these techniques when performed by an independent contractor.

Several economic studies have forecast large benefits from using remote sensing for range inventory, monitoring, and forage condition assessment. For example, a recent (1974) study by the Earth Satellite Corporation and the

Booz-Allen Applied Research Corporation titled "Earth Resources Survey Benefit - Cost Study: Economic, Environmental and Social Costs and Benefits of Future Earth Resources Survey Systems", prepared for the U.S. Department of Interior, Geological Survey predicted annual benefits of 9.0 to 30.6 million dollars in range management. Of these benefits, 5.6 to 22.4 million dollars are attributed to range monitoring, a remote sensing application which has received only limited acceptance to date by range managers. The author generally agrees with the conclusions reached by these studies, but he feels that the magnitude of benefits to accrue in rangeland management in the near future may be somewhat less than projected.

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CURRENT AND FUTURE SATELLITES FOR OCEANIC MONITORING

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1. INTRODUCTION

The application of satellite systems to the marine sciences and oceanic needs has a strong heritage in current and past earth-observing environmental spacecraft. For the marine community the National Aeronautics and Space Administration (NASA) research activities have tended to demonstrate the potential for space techniques, while the National Oceanic and Atmospheric Administration (NOAA) operational satellites have primarily established system spatial and temporal data requirements, as well as some immediate services.

This paper reviews current applications and products from existing operational satellites and the future data and information that will become available before the end of this decade with emphasis on global oceanic data. The companion paper (Teleki and Kover, 1977) will discuss the outlook for the coastal zone.

2. OPERATIONAL SATELLITES

In October 1972 an Improved TIROS^{*} operational Satellite (ITOS-D) was launched by NASA. When the performance of this satellite and sensors were verified, ITOS-D became the responsibility of the NOAA National Environmental Satellite Service (NESS) and was redesignated NOAA-2. Subsequent launches of ITOS-F through -H have maintained the operational polar-orbiting system of NOAA-3 through 5, respectively. Each was launched into a sun-synchronous, 1450-km orbit with two local time crossings of 0900 and 2100 for descending and ascending orbits, respectively.

Two of the three prime sensors on the NOAA series provide oceanic data.^{**} The Scanning Radiometer (SR), which had been operational on other satellites prior to the NOAA series, provides both direct readout data via the Automatic Picture Transmission (APT) system (Popham and Thomas, 1977) and global data via on-board recording for central processing. The SR provides visible region (520 to 730 nm) and thermal infrared (10.5 to 12.5 μ m) nadir spatial resolutions of 4 and 7.5 km, respectively. The other sensor is the Very High Resolution Radiometer (VHRR), also a two channel instrument, with spatial resolution of about 1 km in both the visible 600 to 700 nm and infrared (10.5 to 12.5 μ m) regions. Data coverage is more limited than the SR, with the data directly received when within approximately 3600 km of the NESS Command and Data Acquisition Stations at Wallops Island, Virginia; Fairbanks, Alaska; and Redwood City, California. Additionally, data can be recorded for about 8 to 9 minutes per orbit, allowing a programable sampling of data from other geographical areas around the globe. Examples of the data from these two sensors are given in section 3.

Geostationary Satellites at 36,000 km altitude provide data from areas as large as 100° in latitude and longitude every 30 minutes. The NASA research satellites are designated as the Synchronous Meteorological Satellite (SMS) with SMS-1 launched in May 1974 and SMS-2 in February 1975. The SMS-1 and 2 systems have been used operationally by NOAA. The operational versions of this satellite used by NOAA, are designated as the Geostationary Operational Environmental Satellite (GOES) with GOES-1 launched in October, 1975, and replacing SMS-1 as the operational

^{*}TIROS - Television Infrared Observation Satellite.

^{**}The third sensor is the Vertical Temperature Profile Radiometer (VTPR) designed to measure the vertical temperature structure of the atmosphere. Such sounding instruments are fundamental to marine weather analysis and forecasting, but are not considered here.

satellite. Currently, GOES-1 is positioned above the equator at 75° West longitude and SMS-2 at 135° West longitude.

Both NASA and NOAA geostationary satellites carry a two-channel Visible and Infrared Spin-Scan Radiometer (VISSR) that provides day and night (infrared channel only) imaging of a major portion of the Western Hemisphere. Visible, 1 to 8-km resolution imagery (550 to 750 nm) and infrared 8-km resolution imagery (10.5 to 12.5 μ m) are routinely available every 30 minutes.

3. CURRENT APPLICATIONS AND PRODUCTS

Data from the SR, VHRR and VISSR are processed and made available to the operational and research communities. Such data and data products discussed below can be obtained by inquiry to

Satellite Data Services Branch
Environmental Data Service (EDS)
National Oceanic and Atmospheric Administration
Washington, DC 20233 U.S.A.

These data are applicable to oceanic frontal systems and water mass analyses, sea surface temperatures and ice analyses. Only those current products which are oceanic in nature are illustrated herein. Coastal and Great Lakes regional products are not reviewed.

On a routine basis the SR data is processed in a fully automated computer procedure called Global Operational Sea Surface Temperature Computation (GOSSTCOMP). This product is considered more fully by Kalinowski et al (1977). Temperature retrievals are derived by statistical analysis and quality control techniques applied to provide an effective Sea Surface Temperature (SST) over 100-km intervals of the global ocean. The basic product is a daily set of 5000 to 6000 observations of SST covering both hemispheres. Fig. 1 is an example of the GOSSTCOMP product. In addition to individual observations, other products generated include: (1) global analysed SST fields accessible on computer disk storage, (2) hard copy displays of portions of this analyzed field, and (3) a permanent archive to EDS of the analyzed field.

The VHRR imagery shown in Fig. 2-a serves as the data source for several products.* Research on the life cycles of both cyclonic and anticyclonic eddies are conducted from genesis to destruction specific eddy systems have been observed and describes in terms of development, separation, drift, recapture, and destruction over periods as long as a year.

VHRR images are used also operationally. Fig. 2-b is an example of the weekly NOAA/NESS Gulf Stream Analysis, derived from analysis of several days imagery and is distributed by National Facsimile and mail. This product is used by fisheries, maritime transportation, recreation, and as an input into operational oceanic current analysis of the U.S. Coast Guard Search and Rescue Operations.

Another major VHRR derivative is sea ice analysis. Mapping of ice coverage in both the Arctic and Antarctic has been accomplished since the early 1960's, but with the 1-km resolution of VHRR, seasonal products describing ice type and boundaries are prepared. Fig. 3-a is a VHRR image of the Bering Sea, Bering Strait and Chukchi Sea region and the analysis from this and other images shown in Fig. 3-b. Although the ice thickness cannot be measured directly using satellite imagery, the gray tones of the picture, when combined with multiple images and the analyst's experience, can provide good estimates of the age and thickness of the ice.

The availability of oceanic data from environmental satellites designed primarily for meteorological applications is certain to continue over the next decade just as it has during this decade. The papers by Heacock (1977), Leese (1977), and Jones (1977) discuss the past and future status of the meteorological satellite effort, a status which includes an ever increasing awareness and recognition of marine needs. The joint evolution between the current operational program and the future oceanic research satellites will permit the transition from marine needs to marine requirements to marine operations. These future satellites are presented in Section 4.

*The warm Gulf Stream shows dark in this image, while cooler water is lighter in tone.

4. 1978 - A SPACE FOCUS FOR OCEANOLOGY

The majority of earth-oriented sensors that have provided data from space on the oceans have been multi-discipline sensors, responding to requirements from several scientific or user related interests. Two NASA satellites, the SEASAT-A and Nimbus-G spacecraft, will carry instruments solely dedicated to oceanic measurements. A third satellite, TIROS-N, to be launched by NASA, will become the operational proto-type for polar-orbiting spacecraft, replacing the current NOAA series. The merging of results from these three systems, all scheduled for 1978 launches, will create a sharp focus on the potential of space for specific oceanic data needs. The outcome of this focus will impact the selection of sensors for marine operations in the mid-80's. This section briefly describes these ocean sensors on the specific spacecraft and the next section will deal with potential applications and experiments.

4.1 THE DEDICATED OCEANIC SENSORS

A May, 1978, launch is planned for SEASAT-A which will orbit in a non-sun-synchronous, 800 km altitude, 108° inclination orbit. As such it will not have the usual polar coverage of many earth-observational satellites. However, the companion satellite, Nimbus-G, will have polar coverage (99.28 inclination) with its 955 km altitude sun-synchronous orbit. Equatorial ground-track separation for successive orbits on both satellites exceeds 2700 km. The orbit of Nimbus-G repeats every 5.7175 days as compared to 152 days for SEASAT-A. This SEASAT-A orbit will have a nominal ground track grid separation of 18.5 km at the equator.

Six oceanic sensors will be on SEASAT-A and Nimbus-G. Four are microwave instruments of which three are active. Three instruments are passive radiometers, two operating in the visible and infrared region, and the other in the microwave region. The latter instrument is designated as the Scanning Multichannel Microwave Radiometer (SMMR). Identical SMMR's will be on both SEASAT-A and Nimbus-G. To summarize, the five SEASAT-A instruments include a radar altimeter, a Seasat-A Scatterometer System (SASS), a Synthetic Aperture Radar (SAR), a Visible and Infrared Radiometer (VIR) and the SMMR previously noted.* Nimbus-G will carry two passive oceanic instruments, the SMMR and the Coastal Zone Color Scanner (CZCS).**

The instrumentation on SEASAT-A was discussed by both McCandless (1975) and Sherman (1975) at the Tenth International Symposium on Remote Sensing of Environment. Details of the CZCS are presented by Hovis (1977) in this Eleventh Symposium. For this reason only a summary of the four microwave instruments and the Ocean color sensor is given here.

A short pulse (3 nanoseconds) radar altimeter operating at 13.5 GHz frequency was the first instrument selected for SEASAT-A. Because the sensor looks only at nadir (its swathwidth is between 1.8 and 12 km, depending on sea state), the orbit of SEASAT-A has been tailored to support the geodesy requirements of the altimeter. The precision of the altimeter measurement is expected to be 10 cm rms over seas with a significant wave height from calm to about 20 m. Precise spacecraft tracking is needed for geodesy, currents and storm surge analyses. Processing of the altimeter pulse will yield an estimate of significant wave height to ± 0.5 m or 10% whichever is larger over seas from calm to 20 m.

The SASS is an active microwave instrument which illuminates the sea surface with four-fan shaped beams (two orthogonal beams each 500 km wide on each side of the SEASAT-A ground-track). The amount of energy returned provides an estimate of surface wind magnitude and direction. The transmitted frequency is 14.6 GHz with the returned energy shifted slightly due to doppler effects. The doppler shift aids in establishing a spatial resolution of 50 km over a region from 230 km to 730 km on either side of the spacecraft. Surface winds are to be determined to ± 2 m/sec or 10% in magnitude and $\pm 20^\circ$ in direction. With less precision the SASS can measure winds out to 960 km from the spacecraft. The range of winds to be measured is from 3 to 25 m/sec.

* SEASAT-A will also carry a laser retroreflector, and tracking beacons for precise orbit determination but will not be discussed here. The VIR is identical to the NOAA series SR, except for modification for orbit altitude change and a digital down-link tailored for the signals associated with surface phenomena, rather than clouds. VIR is on SEASAT-A for feature identification, and will not be discussed further.

** The non-oceanic instruments on Nimbus-G include the Earth Radiation Budget (ERB) radiometer, the Limb Infrared Monitoring of the Stratosphere (LIMS) sensor, Stratospheric Aerosol Measurement (SAMII) sensor, the Solar and Backscatter Ultraviolet/Total Ozone Mapping System (SBUV/TOMS), and the Temperature-Humidity Infrared Radiometer (THIR).

The L-band (1.275 GHz) SAR will look to the starboard side of SEASAT-A centered 20° off nadir with a swathwidth of 100 km. The length of the track is determined by the receive-station-view duration with 4000 km being the maximum. A spatial resolution of 25 m needed for wave analyses will generate a very high data rate so that on-board recording will not be used. Thus, data only within view of Rosman (North Carolina), Goldstone (California), and Fairbanks (Alaska) will be collected. Waves and wave spectra to oceanic wavelength of 50 m or greater can be measured with SAR, along with sea ice features, possible iceberg detection, wave-land interfaces and penetration to the surface through major storms such as hurricanes.

Both satellites will carry the SMMR sensor operating at frequencies of 6.6, 10.7, 18, 21 and 37 GHz. The spatial resolution ranges from about 100 km at 6.6 GHz to 22 km at 37 GHz. The three primary classes of data obtained from SMMR are Sea Surface Temperature (SST), sea ice mapping and surface winds. Liquid water and water vapor are potentially measurable as well and will be used to formulate pathlength attenuation corrections for the altimeter and SASS, respectively. SST is to be measured to $\pm 2^\circ \text{K}$, an important first step to determining SST under cloudy sky conditions. The magnitude of the surface winds will be measured to $\pm 2 \text{ m/sec}$ or 10% from 7 m/sec to about 40 to 50 m/sec. The SEASAT-A SMMR will scan the starboard side of the spacecraft, aft-viewing, with a constant 42° angle from nadir. The scan angle is from about 0° to 50° from the aft-starboard resulting in a swathwidth of about 600 km. The Nimbus-G SMMR will also scan at a constant 42° angle from nadir but will look forward and scan $\pm 25^\circ$ with respect to the groundtrack. The resulting swathwidth is about 725 km. The 42° angle from nadir for both SMMR systems gives a constant 45° angle of incidence at the surface due to the earth's curvature. The SEASAT-A SMMR coverage was chosen for maximum overlap with SASS.

Data from the microwave sensors will be recorded on-board and telemetered to one of the previously noted receiving stations. The exception will be the SAR data, which can only be transmitted directly. Hence, global coverage is from three of the four microwave instruments on SEASAT-A and the SMMR on Nimbus-G.

The quantitative measurement of ocean color will be available in four high spectral resolution (20 nm) channels of the six channel CZCS on Nimbus-G. The two remaining channels provide data on surface features, one for SST and the other for land-sea interface definition and ocean surface anomalies. The channels are centered at 443, 520, 550, 670, and 750 nanometers and at 11.5 micrometers. The surface resolution is approximately 825 meters and the total swathwidth exceeds 1500 km. The scanner mirror can be tilted in 2° increments forward or backward through a maximum of 20° with respect to nadir about the spacecraft pitch axis. This aids in avoiding sun glitter.

4.2 TIROS-N OPERATIONAL SENSORS

The third generation of polar orbiting operational environmental satellites will be the TIROS-N system. It is designed to provide improved data for meteorological warning and prediction, oceanic and hydrologic services, and space environmental monitoring. The on-board array of sensors consists of atmospheric sounders, including microwave, infrared, and near infrared; space environmental monitors; high resolution infrared radiometers; and data collection and platform location. Only the latter two systems will be discussed in this paper, although the application of sounders to marine prediction is fundamental to the long-range oceanic effort.

The Advanced Very High Resolution Radiometer (AVHRR) will replace both the SR and VHRR on the current NOAA series. Initially, the AVHRR spectral channels will be (1) 550 - 900 nm for daytime cloud mapping, (2) 725 - 1000 nm for surface water delineation, (3) 3.55 - 3.93, (4) 10.5 - 11.5 and (5) 11.5 - 12.5 micrometers for day/night cloud and sea surface temperature. The fifth channel will not be included on the first TIROS-N, but is being considered for subsequent operational use.

The data from AVHRR will be available in four modes:

1. Continuation of the APT class operation for direct readout to ground stations on a world-wide basis with 4-km spatial resolution for any two channels (channel selection controlled at Suitland, Md.). An important improvement over current APT capability will be the removal of panoramic distortion.
2. Direct readout to ground stations with appropriate digital receiver capability on a world-wide basis of all channels with 1.1-km spatial resolution of the High Resolution Picture Transmission (HRPT).
3. Centrally processed digital and imagery data (Suitland, Md.) for a global record at 4-km spatial resolution on all channels.

*This first channel is to be narrowed to 550 - 700 nm after the first flight.

4. On-board digital recording of selected geographical areas at 1.1-km spatial resolution for potentially all channels. Spacecraft Recording is limited to a maximum of one-quarter orbit per orbit.

The TIROS-N series will include a new capability for operational polar satellites, namely, a Data Collection and Platform Location System (DCPLS). It allows for the on-board recording of telemetered environmental in-situ data from fixed and moving platforms for subsequent transmission to a central processing facility. Doppler processing of the telemetered signal will allow the location of the platform for velocity determination. Table 1 shows the key features of DCPLS. The current plans for agreement among the Centre National d'Etudes Spatiales (CNES), NASA, and NOAA calls for France to be responsible for the space hardware and data processing.

TABLE 1. DCPLS PARAMETERS

System Parameters	Value	Platform Parameters (typical)
Data bit error rate	10 ⁻⁵ to 10 ⁻⁶	Frequency 401.64 MHz
Location accuracy	5-8 km rms	Emitted power 3 W
Wind speed accuracy	±3 mps	Bit rate 400 Bps.
Visibility circle	50 elevation	Message duration 400 ms.
No. of platforms in circle	200 max.*	Message repetition period 60-80 sec.
Total platforms over globe	2000 max.	

*Number of platforms requiring location, velocity determination, and telemetering four sensor channels, visible in a 50° visibility circle. Actual number will depend on mix of platforms.

4.3 DATA AVAILABILITY

The SEASAT-A instrument ensemble will provide 95 percent global coverage in 36 hours for surface winds, temperature and waves. Nimbus-G is comparable and TIROS-N is twice daily. The spatial resolutions associated with each instrument in the above description are viewed in a different manner when coupled with the swathwidth and orbital velocity to define an equivalence with regard to in-situ data.

TABLE 2. EQUIVALENT IN-SITU SEASAT-A DATA REPORTS PER DAY

Parameter	Real-Time	Non-Real-Time
Winds		
Vector-SASS	115,000	192,000
Magnitude-SMMR* (every 50 km)	106,000	177,000
Waves		
H1/2-Altimeter (every 6.7 km)	36,000	60,000
SST		
Temperature-SMMR*	46,000	77,000

*The SMMR data shown is approximately doubled if the data from Nimbus-G and SEASAT-A are combined.

These equivalences are noted in Table 2 and represent near-instantaneous spatial averages rather than point source data temporally averaged. The significant increase in data availability illustrates the importance of both the satellite technique and maintaining and improving the in situ collection methods. Rigorous calibration of the satellite requires the surface program while the surface program is extended spatially by the satellite.

The CZCS is currently scheduled for up to 16 minutes of acquisition time per orbit. With 13.8 orbits per day, more than 200 minutes of CZCS data and imagery will be available daily. This is more than 12×10^7 km² per day. The CZCS data will be received at the three SEASAT-A stations cited previously and at Madrid, Ororral and Santiago. All CZCS data will be processed at the NASA Goddard Space Flight Center (GSFC).

Archiving and distribution for TIROS-N, SEASAT-A, and Nimbus-G marine data will be performed by the NOAA Environmental Data Service (EDS). Data with approximately a 10 to 12-day delay from time of acquisition may be obtained from EDS beginning on or about September 1978 for SEASAT-A. Initial data may be quite limited geographically. After launch there will be at least a 3-month process-proving period in which the sensor electrical units are converted to geophysical units for SEASAT-A. TIROS-N and Nimbus-G data will be available after appropriate checkout and verification. When such research data are ready, it will be available on a user-reimbursable basis from the Satellite Data Services Branch (SDSB) whose address was cited in Section 3.

A special comment on the availability of SAR data is appropriate. Current plans are to collect data from 400-1500 orbits during the first year of SEASAT-A operations. Of these orbits, 260-10 minute passes will be processed to imagery for a total of about 2600 minutes of data the first year. Thus, while the other sensor data will be widely available to the marine community, SAR data will be quite limited.

For those users requiring engineering data records rather than the geophysical data from SDSB, inquiries should be directed to:

Dr. James A. Dunne
Ocean Experiments Manager
SEASAT-A Project
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91103 U.S.A.

5. OCEANIC MONITORING

The array of instruments to be available on satellites beginning in 1978 and beyond will offer a unique opportunity to marine users. This section discusses selected applications and potential uses of data from SEASAT-A and Nimbus-G. All these 1978 instruments have a direct heritage from other earth-orbiting satellites, except for SAR. Because TIROS-N data will be improved but similar to that of the NOAA series, applications of TIROS-N will not be discussed.

5.1 RADAR ALTIMETER

The manner of interaction of the very short radar altimeter pulse with the ocean surface is illustrated in Fig. 4. The swathwidth assigned the altimeter is the time for the altimeter returned pulse to reach maximum signal strength, and thus depends directly on the significant wave height, or "sea state". This rise time, for greater wave heights, is stretched in direct proportion to the height probability density function.

The SEASAT-A altimeter also will measure the distance between the sea surface and the satellite to an expected precision of about 10 cm rms. Altitude information at this level of precision is expected to allow mapping of the static sea level geoid and the dynamic ocean topographic features superimposed upon that geoidal surface. Such features include the dynamic topography associated with geostrophic ocean circulation, tides, wind set-up, storm surges, and barometric pressure effects. The geoid itself will have to be computed by extraction of these disturbing phenomena once those phenomena are understood fully, and will be determined after the orbital distance from the center of mass of the earth has been determined as precisely as possible. Although the orbit may never be calculated to the level of precision of the altimeter, the unmodeled uncertainties in the orbit probably will not have the same time and space distribution as either the real geoidal undulations or the dynamic factors creating ocean surface topography. Analyses of these problems are presently incomplete, but show promise that the dynamic features will be elucidated beyond present understanding.

Gravity anomaly features such as the Puerto Rican Trench shown in Fig. 5 will be observed and refined, and smaller-scaled features due to deep-ocean trenches and corresponding elevations resulting from seamounts, plateaus, and ridges will be detected.

5.2 SCATTEROMETER

The SASS will serve primarily as a low-to-intermediate surface wind-field anemometer. The SKYLAB S-193 sensor capability illustrates in the data of Fig. 6 the potential for SASS to measure surface winds. By use of the orthogonal beams of SASS, the potential exists to measure wind direction as well as magnitude. Fig. 7 illustrates the variation in the back-scattering coefficient as a function of wind direction. However, ambiguities will occur in the data set which will require manual wind field analyses and data from more conventional data sources to remove the ambiguities.

The SASS data, with approximately its 50-km spatial resolution will form a major input into planetary layer studies, especially with regard to meso-scale events. Specific studies of the Pacific Equatorial Oscillation and its effect on the ocean surface may aid in the understanding of such events as the El Nino. Other applications may come from the developments of Gray, et al. (1977).

5.3 RADAR IMAGER

The SAR will be a new Earth observation sensor. Technical design for the SAR on SEASAT-A is different from what might be found on SAR's designed for terrestrial observations. Special processing requirements are found in the papers of McCandless (1977); Bayma, et al. (1977). A more detailed discussion of the application of SAR information to marine applications is in the paper of Shuchman, R.A., et al.

The coherent nature of SAR allows integration in a scene to achieve spatial resolution. However, just as Moving Target Indicator radars, which use doppler information, frequently show trains off the tracks and automobiles in the middle of plowed fields, the analyses of SEASAT-A SAR data will require forethought and care. A spatial resolution of 25m is desired in order to image waves as short as 50 m. But the movement of the wave limits the integration time. Thus, SAR as a sensor will be highly interactive with specific environmental situations.

The most straight-forward application of SAR is for the dynamics and mapping of sea and lake ice. Wave refraction and shoaling, oil spill detection, analyses of wave development in hurricanes, current boundaries under certain conditions, and wave spectra will be among the other applications of SAR. Fig. 8 illustrates the Jet Propulsion Laboratory (JPL) airborne L-band SAR imaging of ocean swells and the digital two-dimensional intensity spectra (related to wave spectra) derived for these waves.

5.4 MICROWAVE RADIOMETER

The SMMR system has a strong heritage in the Nimbus-5 (19.4 GHz) and -6 (37 GHz) scanning radiometers. The data application of the dual-polarization, five-frequency SMMR will be limited to the measurement of surface winds in this discussion. The response of a 19.4 GHz radiometer to the ocean surface with a 290° K temperature for various wind conditions is shown in Fig. 9. This frequency is used because of windfield analyses using Nimbus-5 data shown in Fig. 10 and to illustrate that a multi-frequency system is needed. The Nimbus-5 system is horizontal polarized and was not designed for wind measurements. The data supports the existing theoretical models being developed for the SMMR system.

Fig. 10 (after Sabatini, 1974) has been prepared from Nimbus-5 microwave data for winds from about 3 to 18 m. sec.⁻¹. Using a single frequency and polarization, it is not possible to correct for atmospheric effects* or other environmental variables. The wind field data is from the Fleet Numerical Weather Central (FNWC-Monterey, California) Spectral Model map analysis nearest in time to the microwave coverage (approximately an hour earlier). The SMMR system 10.7 GHz channel will have slightly greater sensitivity to winds than the 19.4 GHz frequency on Nimbus-5. Simultaneous equations will be solved to provide corrected geophysical data, but basically the SMMR 6.6 GHz channel will provide sea temperature, 10.7 GHz winds, 18 and 21 GHz atmospheric corrections, and 37 GHz sea and lake ice.

5.5 COLORIMETER

The CZCS (Hovis, 1977) will have applications extending well beyond those of environmental quality and pollution. The spectral characteristics and instrument design have been chosen specifically to address the measurement of chlorophyll in the ocean. The instrument "depth" for observing below the surface is limited essentially to the first optical depth of the water system, but strong correlations have been found between the characteristics of chlorophyll (concentration) in the first optical depth and the depth to the euphotic zone.

Excluding atmospheric and surface effects, the irradiance reflectance of the ocean as a function of wavelength with chlorophyll concentration as a parameter is shown in Fig. 11 after Smith and Baker. This range of chlorophyll is the major interval important to the oceanic community. Chlorophyll absorption in the blue portion of the spectrum is the basic means of

*The Nimbus-5 radiometry was designed primarily for mapping atmospheric water vapor and sea ice fields. Clear areas only are used in Fig. 10, for averages over about a 100X100 n.mi. area.

discriminating between suspended sediments and chlorophyll, both having increased reflectances in the green and red portions of the visible spectrum.

The effect that chlorophyll has on the color of the ocean has been illustrated by Smith and Baker, (1977) using the (CIE) chromaticity diagram.* This diagram uses the loci of spectrally pure wavelengths based on a standard source. In Fig. 12 this source is noted as "C" and the curve labeled from 450 to 650 nm is the spectrally pure wavelengths. The tristimulus values of reflectance, for the various concentrations of chlorophyll shown in Fig. 11, are plotted on the chromaticity diagram. The oceanic color varies with pigment concentration, and the dominant wavelength for any given concentration is obtained by drawing a line from the standard illuminant "C" through the given chlorophyll concentration to the value on the pure spectrum locus. Thus, for 0.01 mg.m^{-3} of chlorophyll, the dominant wavelength is 470 nm.

These oceanic color changes with chlorophyll concentration will be measured by the CZCS. A major experimental effort to quantify the color changes in terms of the water characteristics (chlorophyll and suspended sediments in particular) will be conducted. Surface, atmospheric, sun, and view angle effects must be evaluated and corrected in order to remotely measure the water characteristics. An initial goal is to measure chlorophyll concentration to within a factor of two over the 0.01 to 10 mg.m^{-3} interval.

6. SUMMARY

Over the last decade research and operational satellites have demonstrated that the spatial and temporal scales provided by earth observing systems can support the needs of oceanology. Indeed, specific oceanic applications using visible and infrared data have been developed operationally for sea surface temperature, major current tracking, limited area ship routing, and lake and sea ice. The satellites planned for launch in 1978 will significantly extend this present capability, expand the knowledge of oceanic dynamics, and increase the operational uses of space technology. The first noteworthy applications will be near all-weather analyses and prediction of surface winds; waves and wave spectra; circulation and oceanic current processes, and surface layer transport; severe storms, storm surge and setup, and tides; surface temperature; oil spills; ice dynamics, mapping and statistics; and determination of the earth's geoid. Significant steps using ocean color (not all-weather) will be accomplished in water mass dynamics, including circulation (both horizontal and vertical), discrimination, identification, and classification; suspended particulates, including sediments and bio-optical state (chlorophyll and potentially estimates on productivity); fisheries utilization; and environmental quality.

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GOSSTCOMP SEA SURFACE TEMPERATURES

4/6/77

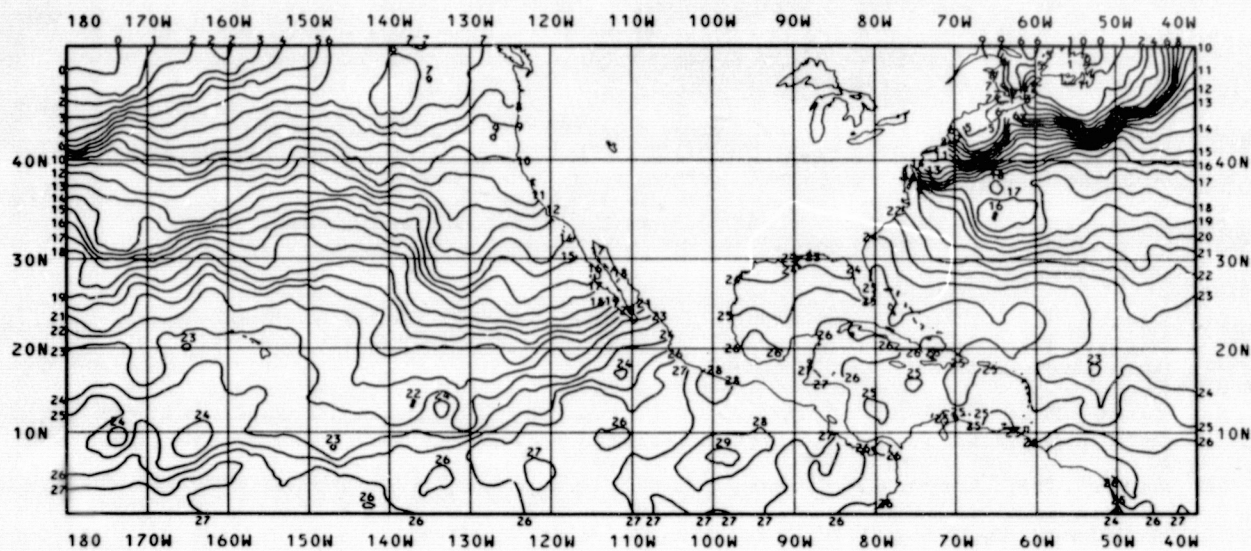


Figure 1. Global Operational Sea Surface Temperature Computation (GOSSTCOMP) for April 6, 1977, derived daily from the NOAA satellite series (NOAA-5 for this analysis) using the Scanning Radiometer (SR). Temperature retrievals are statistically averaged over approximately a 100-km square area.

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Figure 2-a. The NOAA-5 Very High Resolution Radiometer (VHRR) thermal image of the Western North Atlantic shows the major coastal waters surface features, including the Gulf of Mexico Loop Current and the Gulf Stream. Spatial resolution is 1 km at nadir. These data are used routinely in the preparation of marine products, such as the one in Figure 2-b.

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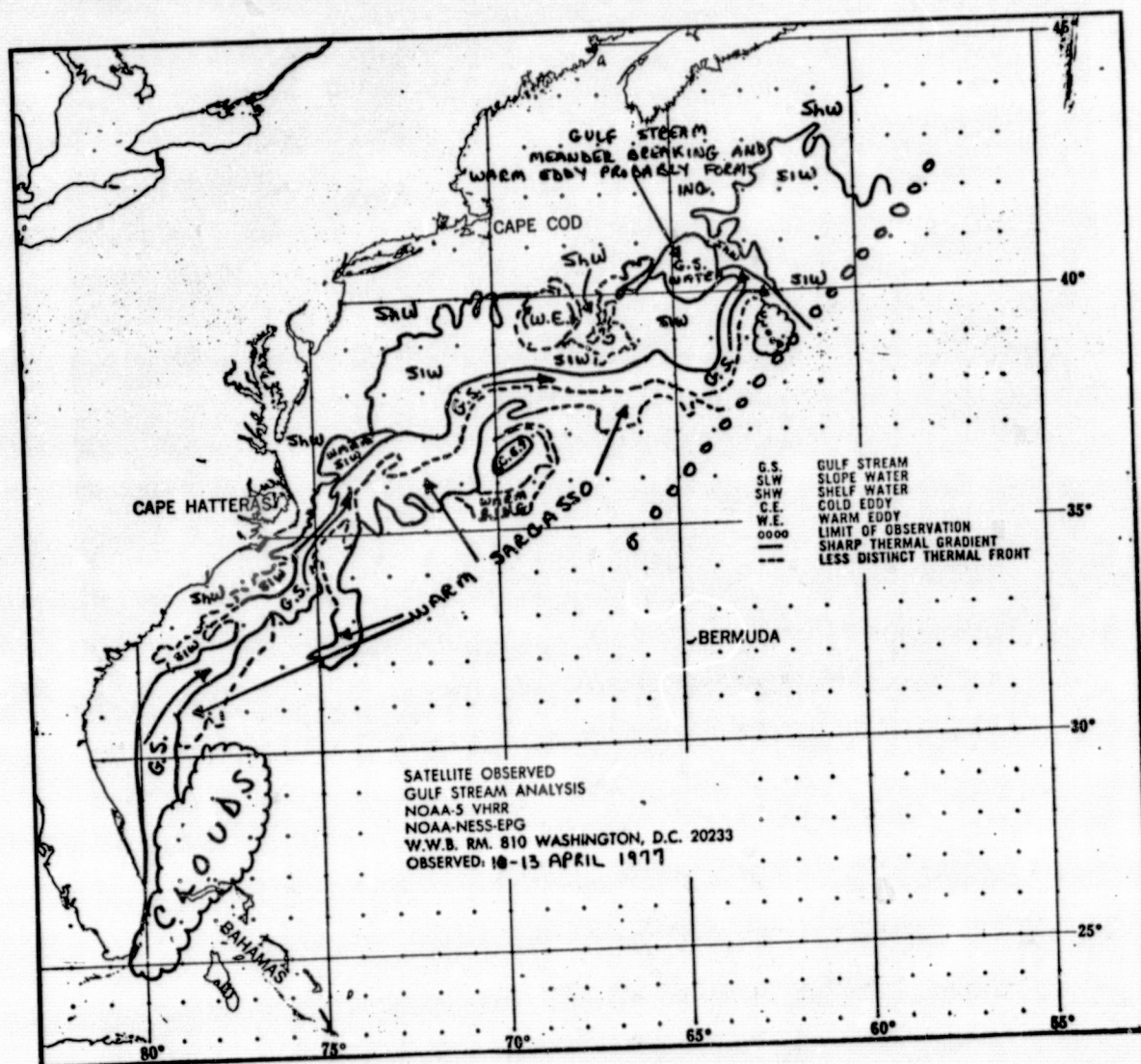


Figure 2-b. A satellite derived Gulf Stream Analysis is prepared weekly using several images of the type shown in Figure 2-a. The thermal data define the water masses and their associated fronts off the East Coast of the U. S., and are not used for absolute temperatures.

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Figure 3-a. NOAA-4 VHRR visible image of ice in the Bering Sea, Bering Straits, Chukchi Sea and East Siberian Sea on March 17, 1976.

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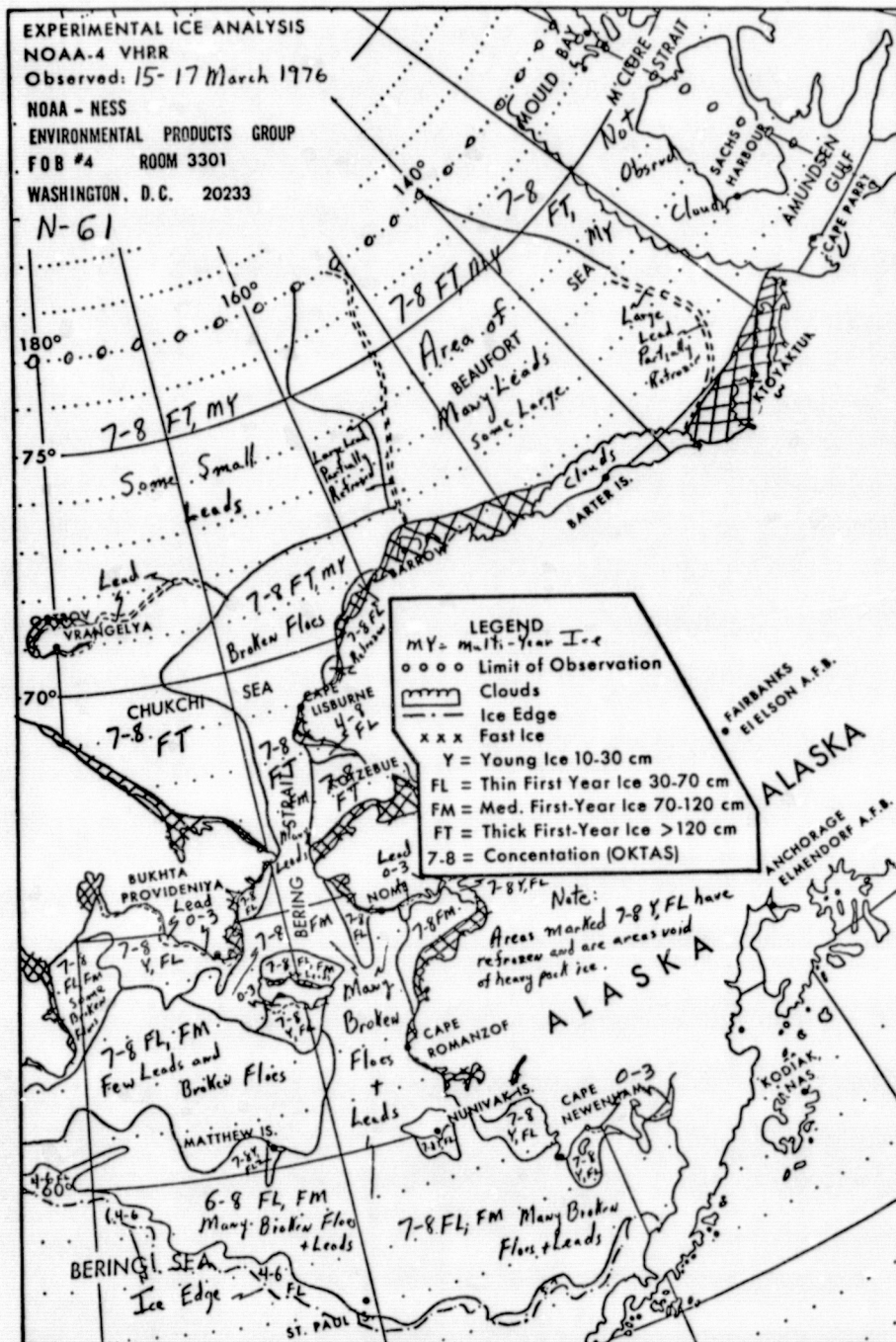


Figure 3-b. Ice field analyses using imagery as shown in Figure 3-a are prepared and distributed weekly during the ice season. The data are quantified according to the Legend in the figure.

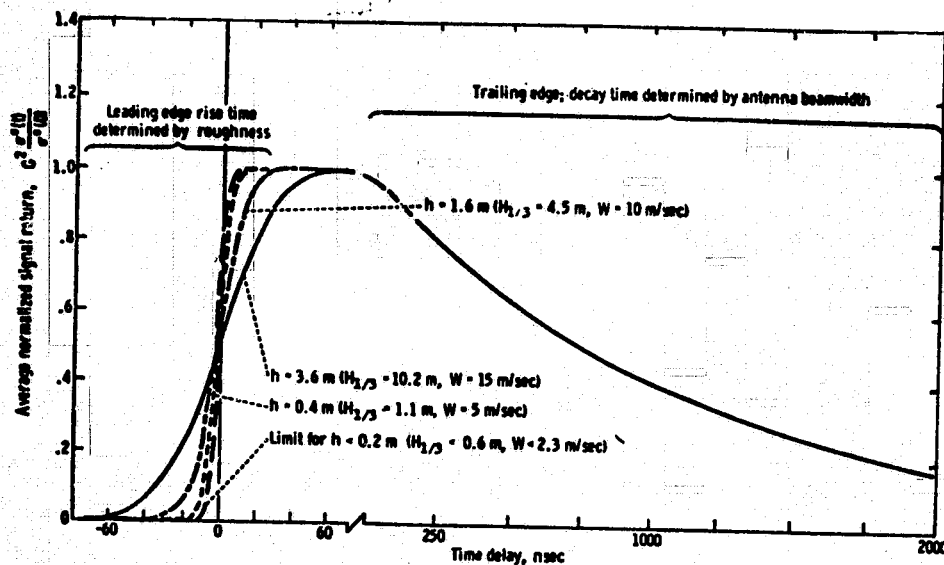


Figure 4. Average radar cross section as a function of time for several wind and wave conditions for a nadir-looking, short-pulse radar. ($H_{1/3}$ is the significant wave height and W is windspeed.) Note the break in scale of the abscissa.

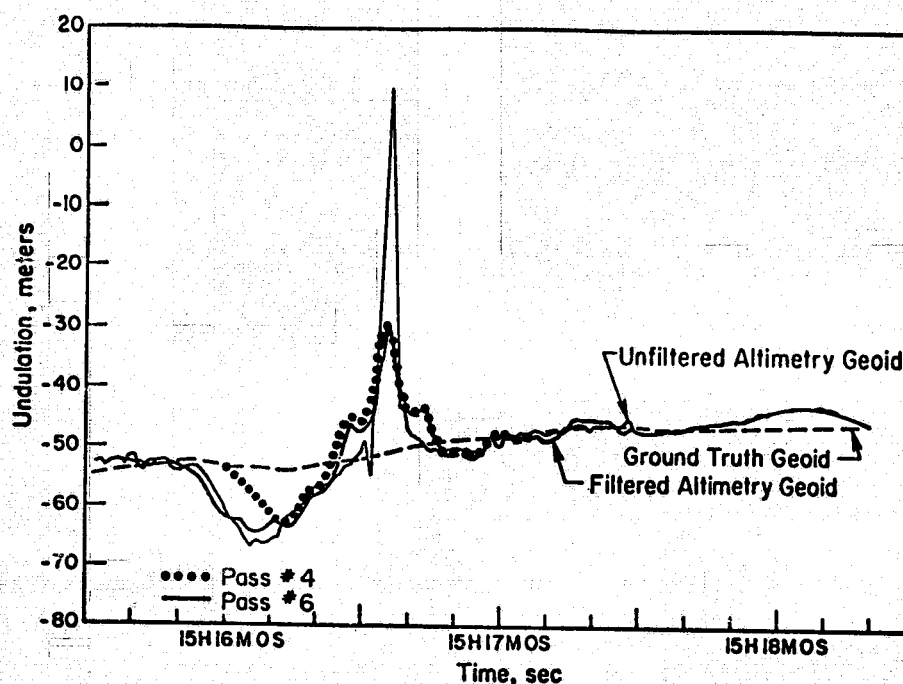


Figure 5. Comparison of the SKYLAB altimeter geoid profiles over the Puerto Rico Trench and land mass. After Mourad, et al., 1975.

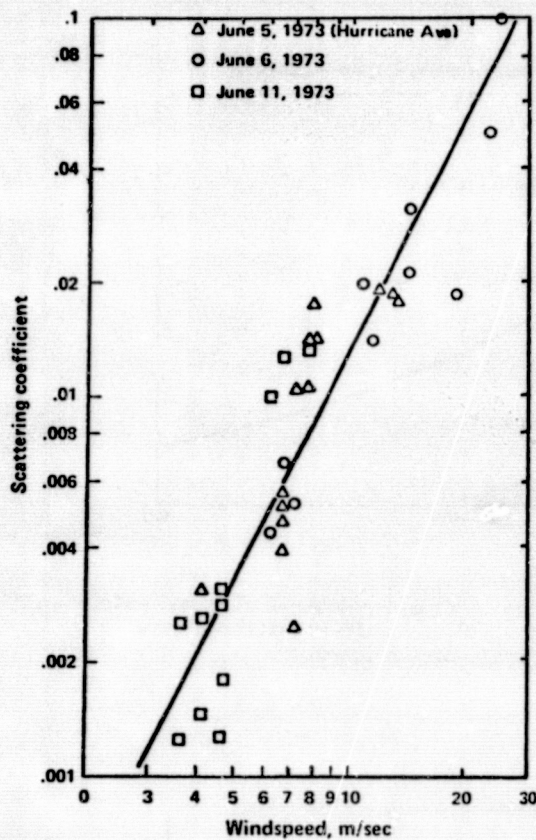


Figure 6. The SKYLAB scatterometer measured backscattering cross section (solid line) compared to *in situ* measurements of wind at sea (horizontal polarization, 50° angle with vertical).

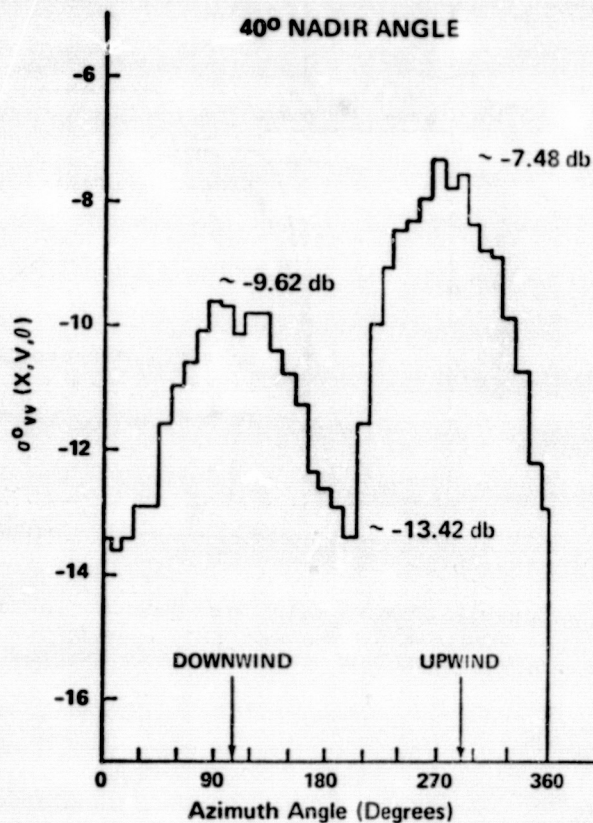


Figure 7. Radar backscattering cross section, σ_{vv} , as a function of azimuth angle for a 13 m/s windspeed measured by the Langley AAFE RADSCAT program.

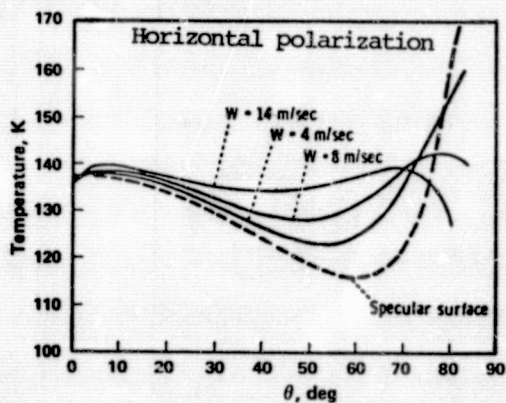
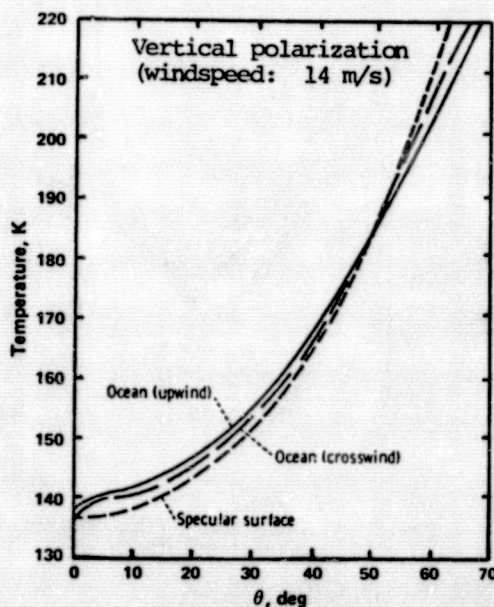


Figure 9. Theoretical microwave brightness temperature as a function of incident angle with the wind-roughened ocean surface (capillary waves) as a parameter. A frequency of 19.4 GHz, and water temperature of 290°K apply. Horizontal (left) and vertical (right) polarizations are shown.



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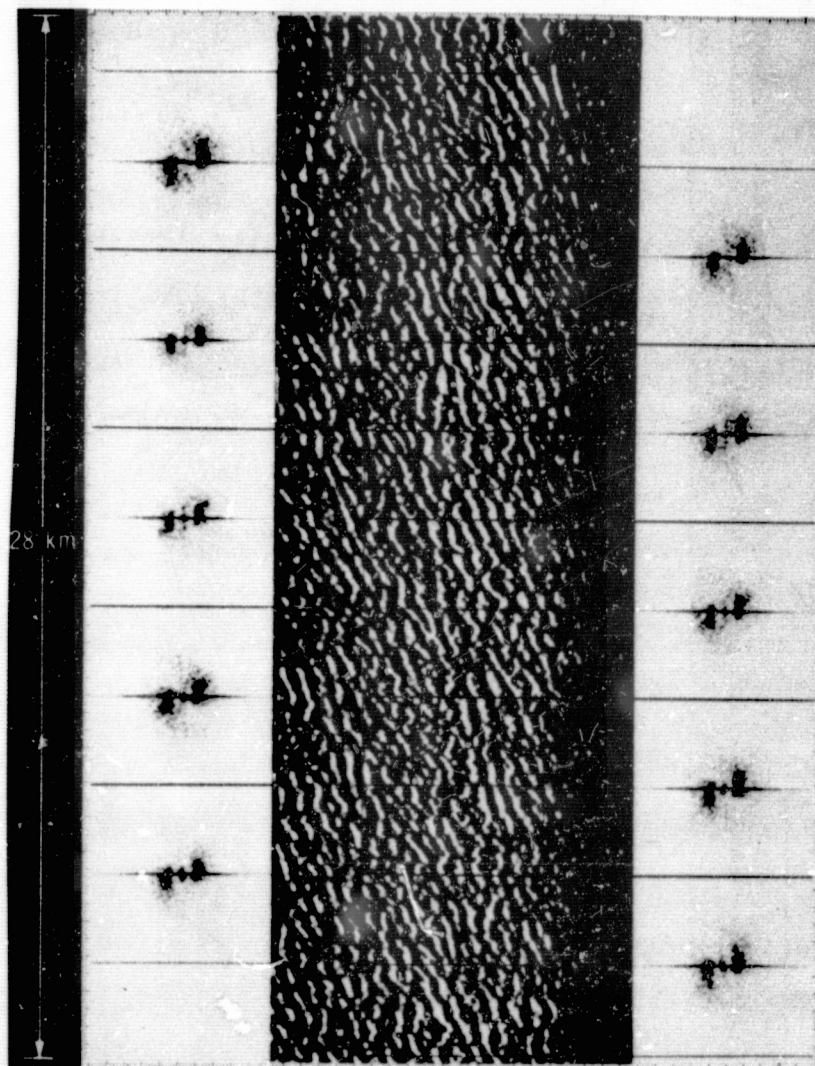
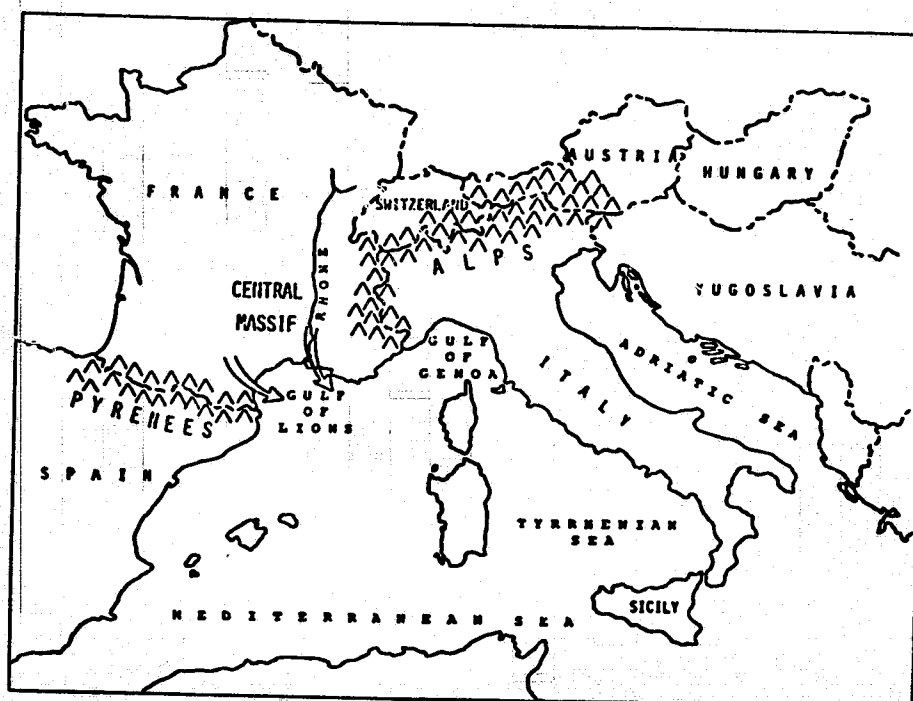


Figure 8. NASA Jet Propulsion Laboratory (JPL) imaging radar scene of ocean swells and the derived digital 2-D intensity spectra and enhancement. Courtesy of Charles Elachi, JPL.

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The Mediterranean Area

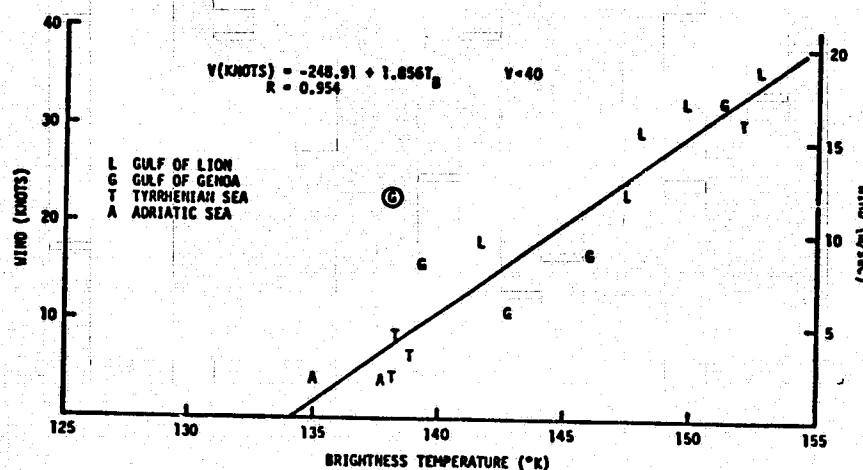


Figure 10. Scatter diagram of wind versus microwave brightness temperature, T_B , for specific areas in the Mediterranean Sea. Each letter represents an average of all wind and T_B observations in clear areas averaged over 100 n.mi. square areas. Data collected by the Nimbus-5, 19.4-GHz radiometer. Sabatini, 1974.

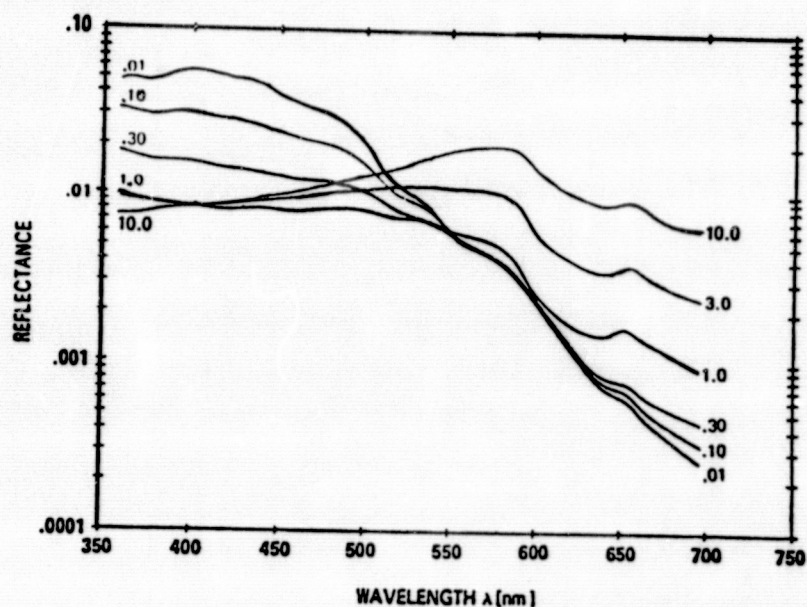


Figure 11. Theoretical irradiance reflectance as a function of wavelength for various values of chlorophyll pigment ($\text{mg pigment} \cdot \text{m}^{-3}$). Calm sea conditions and no intervening atmosphere. Smith and Baker, 1977.

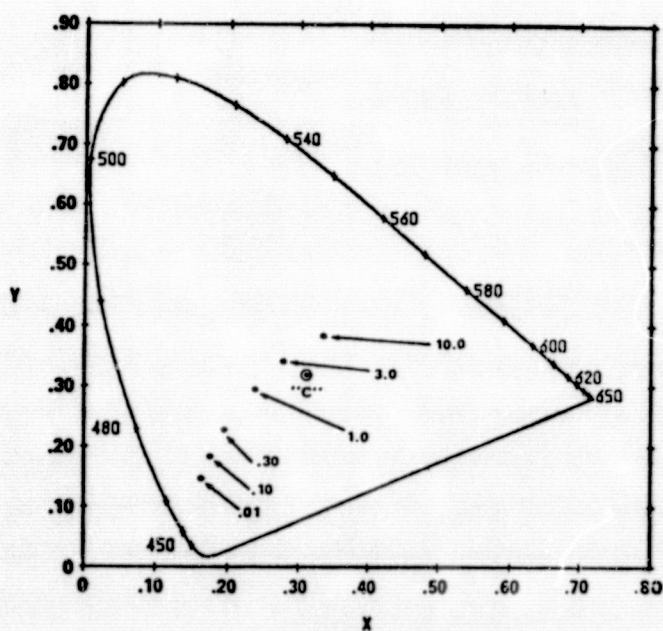


Figure 12. CIE chromaticity diagram showing the loci of spectrally pure wavelengths by the curve labeled from 450 to 650 nm, based on standard source labeled "C" as the achromatic stimulus. The tristimulus values of reflectance for the values of chlorophyll pigment concentration in Figure 11 are plotted and labeled. Smith and Baker, 1977.

OUTLOOK FOR REMOTE SENSING IN THE COASTAL ZONE

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During the next decade, increasing amounts and diverse types of information will be needed for management of the coastal zone. Efficient management is predicated not only on a sound data base, but on rapid reliable updates of the information system as well. These updates are achievable if the surveying systems can be operated economically and are able to collect data at short recurrence intervals.

Among the many ways to acquire information, remote sensing should be ranked high, especially in the coming decade. As Landsat's optical sensors opened up new frontiers of applied science in the 1970's, so will microwave technology in the 1980's as it graduates to spaceborne status. Main results of the exploratory experiments with an altimeter and scatterometer on Skylab, an integrated package of two passive and three active microwave sensors were designed for Seasat-A, which will be launched in 1978. The Seasat-series of satellites was conceived by users and dedicated to the study of ocean dynamics and coastal processes. NASA (National Aeronautics and Space Administration) plans to culminate this project in a six-satellite operational phase in the late 1980's or early 1990's. Seasat-A instruments will obtain data on waves, wind, fresh water and sea ice, and sea surface temperature, and a limited amount of terrestrial information. In 1973, NASA will also launch Nimbus-G carrying the Coastal Zone Color Scanner (CZCS), and a passive microwave radiometer. In the same year, AEM-A (Advanced Explorer Missions for heat-capacity mapping) will begin to acquire information on water surface temperatures and effluents, soil moisture and plant stress, and lithology. Complementary projects in the manned Shuttle program will test the usefulness of several sensor combinations to selected disciplines and evaluate effects of different microwave frequencies, polarizations and antenna orientations. The Shuttle may become quite useful to monitoring disasters, although its principal benefits are in onboard scientific and engineering experimentation.

Several aspects of the coastal zone are expected to benefit from these new developments. Among those applications that are now deriving benefits are shoreline surveys and wetlands mapping, based on photogrammetric techniques applied to aerial photographs and LANDSAT imagery. Orbiting NOAA (National Oceanic and Atmospheric Administration) and geostationary (SMS-GOES) weather satellites have contributed to public safety in low-lying coastal areas by helping to predict movements of weather systems and the landfall of storms. Inundation limits of storm surges have been mapped with Landsat MSS (Multispectral Scanner) imagery. As data from the GEOS-3 (Geodynamics Experimental Ocean Satellite) and Seasat-A altimeters become available, storm surge elevations and gradients should be quantitatively determinable, thus improving predictive algorithms now in use.

Radiometers, such as the VHRR (Very High Resolution Radiometer) on NOAA satellites and the ESMR (Electrically Scanning Microwave Radiometer) on Nimbus-5, together with visible and infrared (IR) systems, have helped to improve our understanding of sea ice dynamics and the characteristics of shear zone ice. Pack ice type and concentration correlate well with satellite brightness temperatures. The one-kilometer resolution in VHRR imagery is an order of magnitude improvement over IR data, however, further advances in the capability of the weather satellites to differentiate among ice, snow and clouds are still needed.

After decades of study, beach erosion and unwanted accretion of sediments near harbors and waterways are two critical problems still facing coastal engineers. The process by which sediments are transported is complex, and to date, remote sensing has contributed only to the postfacto surveys of shoreline changes, rather than to the understanding of the process itself. Charting sediment plumes along the coast by means of airborne and Landsat multispectral systems has not given quantitative answers to the questions of how much sediment is in motion and at what rate. The Seasat-A imaging radar, which will provide information on directional wave spectra, is expected to materially help in quantifying littoral transport of sediments, as such data are applied to coastal wave propagation and transformation theories. Whether the observed plumes are actually suspended sediments or expressions of biological activities, is debatable without surface measurements. "Whitening" observed on Landsat MSS imagery was interpreted to be carbonate precipitation, but algal growth or chlorophyll on the water surface could provide

similar signatures. The Nimbus-G CZCS, using an MSS-type system with narrower spectral bands than does Landsat, is designed to differentiate among these phenomena. Corollary information from radiometers on sea-surface temperature should help to determine the nature of suspended matter observed. LAGEOS (Laser Geodynamics Satellite), launched in 1976, uses 426 retroreflectors to detect changes in the movement of the Earth's surface and could potentially improve beach erosion studies by monitoring shoreline changes more accurately.

Optical and microwave techniques are applicable to pollution monitoring as well. Thermal pollution is commonly charted by means of airborne infrared sensors; spaceborne IR sensors to date have no equivalent resolution, but this is an area of sensor engineering where improvements are anticipated. Pollutants, such as oil, are demonstrably chartable using the Fraunhofer Line Discriminator which detects fluorescence, or with radars which measure a difference in back-scatter.

Other nearshore problems exist in the area of fishing, where information on the type and quantity of fish being taken is scant. Because there are no planned or existing remote sensors able to detect subsurface activities, such as schools of fish, directly, monitoring of fishing areas for their efficient management has to rely on indirect estimators. Studies in the Gulf of Mexico related fishing areas to the presence of sediment plumes. What kind of fish are being harvested may be determinable for vessel characteristics; interest in surveying them has increased, now that, the U.S. has legislated a 200-mile economic zone. Microwave sensors are being considered for conducting such surveys.

The emphasis in designing future technology is on studying dynamics processes rather than on mapping observable phenomena. Passive techniques on measuring natural reflectances are being gradually replaced with active techniques, in which the experimenter can manipulate characteristics of the sensors to maximize his information return. These developments will be particularly useful to coastal zone remote sensing.

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COASTAL WETLANDS: THE PRESENT AND FUTURE ROLE OF REMOTE SENSING

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ABSTRACT

During the past decade, there has been a rapid expansion of remote sensing research and technology development related to coastal wetlands. As a result of this research, all of the 23 coastal states have ongoing or completed wetland inventories, most utilizing aerial photographs as the data source for producing a variety of map products with varying scales, formats, classification systems and intended uses. The U.S. Geological Survey is increasing emphasis on map production and revision for the coastal zone. The new U.S. Fish and Wildlife Service National Wetland Inventory is intended to provide a standardized method for comparison of wetlands on a national basis - it too will use available aerial photographs as a basic data source.

At present, satellite data is not used for operational mapping of coastal wetlands because of resolution and geometric constraints. In the future, however, satellite data may provide an accurate reliable and economical source to update wetland inventories and to monitor or evaluate coastal wetlands. The technological improvements accompanying the development and launch of Landsat C and D and the Space Shuttle promise to make satellite digital data a more powerful tool to supply information for future management decisions for coastal wetlands.

INTRODUCTION

The surge of interest in coastal-zone resources during the past decade has been accompanied by a rapid expansion of related remote sensing research and technology development. Wetlands are a primary focus of this interest; in recent years our understanding of wetland values has increased and Federal, State and local governments have enacted legislation to protect wetlands. These laws generally require classification and inventory of wetlands as the first step in the protective process and, thus, they have greatly increased the need for better and more efficient tools to accomplish this task.

The U.S. Fish and Wildlife Service (FWS) 1956 inventory of wetlands (Shaw and Fredine, 1956) estimated that there were 29.9 million hectares of wetland in the United States: of these, 1.62 million hectares were coastal fresh wetlands and 2.14 million hectares were coastal saline wetlands. The inventory included only wetlands in the conterminous United States and most wetlands less than 16.2 hectares in size were excluded from the survey. Since 1956, many hectares of wetland habitat have been lost as a result of increased pressure for housing, industrial and agricultural development. This loss of coastal wetlands, especially in highly industrialized states such as New Jersey, New York, and Delaware, has added additional impetus to the development of mapping, inventory, and monitoring techniques.

This paper presents an overview of the present and future use of remotely-sensed data for coastal wetland inventory, mapping, and evaluation. For the purpose of this paper, coastal wetlands are defined as "tidal" wetlands and the definition of wetland is that suggested by FWS (Cowardin and others, 1976):

"wetland is defined as land where the water table is at, near, or above the land surface long enough to promote the formation of hydric soils and to support the growth of hydrophytes. Permanently flooded lands lying beyond the deep-water boundary of wetland are referred to as aquatic habitats.

In certain wetland types, vegetation is absent and soils are poorly developed or absent as a result of frequent and drastic fluctuations of surface-water levels, wave action, water flow, turbidity or extremely high concentrations of salts or other substances in the water or substrate. Wetlands lacking vegetation and hydric soils can be recognized by the presence of surface water at some time during the year and their location within, or adjacent to, vegetated wetlands or aquatic habitats."

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Simply stated, the major task for the coastal states and other concerned agencies and organizations is to map, inventory and/or evaluate the coastal wetlands of the United States in order to ascertain the present amount of wetland, to measure future gains or losses in wetland acreage, and to develop priorities for wetland preservation so that the coastal wetlands can be protected as a valuable natural resource. Looked at closely, this task is far more complex than it appears at first glance. Some of the associated problems are discussed below. The remainder of the paper summarizes the role of remote sensing in accomplishing this task.

THE PROBLEMS

Definition

Definition and classification are usually prerequisites for wetland mapping and inventory, either because of legislative requirements or as a means to provide the maximum amount of information to the resource manager. Legal definitions of wetland tend to lack clarity, largely because wetlands are dynamic ecosystems with a complex inter-relationship of hydrology, soils, and vegetation. There have been several approaches to definition of "coastal" and of "coastal wetland." The Coastal Zone Management Act (CZMA) of 1972 (P.L. 92-583) defined the coastal zone as the coastal water and adjacent shorelands. The zone extends "inland from the shoreline only to the extent necessary to control shorelands, the uses of which have a direct and significant impact on the coastal waters." The individual states must select their inland boundary based on this definition. A state may choose to use a vertical distance above mean high water (MHW), a township line or paved road, or the inland border of all coastal counties provided the boundary meets the requirements of the definition. There is no requirement for uniformity from state-to-state. The definition of "coastal wetlands" (not included in the CZMA) is subject to similar variations in the scientific or legal literature. The term may include all wetlands lying within the "coastal zone", all "tidal" wetlands lying within the "coastal zone", all "tidal" wetlands per se, or only vegetated (marsh, swamp) wetlands lying within the "coastal zone" or "tidal" in nature. At present, there is no universally accepted definition of wetland or coastal wetland.

Classification, scales, formats and boundaries

Individual states have modified existing systems or developed their own wetland definition and classification system because no existing classification system has proved adequate. Such systems may be based on the use of remotely-sensed data as the primary data source or merely as a supplement to field inventory procedures. The use of different definitions and wetland classifications means that the resulting wetland maps or inventory products are not mutually compatible. They have different scales, formats, minimum mapping units (MMU) and classes, and do not allow for valid comparisons of acreage, wetland type, or vegetative composition on a regional or national basis.

USGS 7.5-minute quadrangles and orthophotoquads can be used as an example to illustrate format and content, as they are often used as base maps for coastal wetland mapping. On the standard line map, the following wetland types (hydrographic features) are displayed with appropriate symbols: marsh, submerged marsh, swamp, submerged swamp, mangrove, rock or coral reef, and coastal beaches-backshore beaches (sand or gravel) and tidal or foreshore flats (sand, gravel, mud, shell). The shoreline shown on topographic maps is the approximate line of MHW except in areas of marsh grass, mangrove, or other marine vegetation where the apparent shoreline at the outer edge of vegetation is shown in lieu of the MHW line. Vegetative categories are shown by unbounded symbols, so that national map accuracy standards (NMAS) cannot be applied to the wetland/upland boundary. Orthophotoquads are black-and-white (B/W) rectified photomaps prepared in standard 7.5-minute quadrangle format with little or no cartographic treatment. Where available, they provide an excellent base map for detailed wetland mapping.

When wetland maps are utilized for landowner information and regulatory permitting procedures, accurate boundaries are critical and mapping scales are larger than 1:24,000 (for example 1:2400 in New York, New Jersey and Delaware). Where the maps or inventories serve primarily to locate, classify, and measure wetlands, the exact placement of the boundary is less crucial and the mapping scales may be smaller. The wetland/upland boundary and the MHW boundary are most often used for legal purposes. MHW is a tidal datum plane defined as "the average height of the high water over a 19-year period" (Boon and Lynch, 1972). MHW generally marks the boundary between state-owned and privately-owned, state-regulated property. McEwen and others, 1976, have an excellent discussion of the difficulties of using MHW as a legal boundary. Several attempts have been made to tie vegetative indicator species to the MHW line (Brown, 1977; Guss, 1972) but it is clear that if vegetative criteria are used, they must be established

on a state-by-state basis using surveys carefully referenced to tidal gages. The wetland/upland boundary is generally determined by the change in vegetative composition from wetland to terrestrial species. Where the transition zone is broad, the experience of the photo-interpreter or the ground surveyor is a factor in boundary placement. The Environmental Protection Agency (EPA) has recently let a contract to Oregon State University to study the species composition and soils of the transition zones and relate them to tidal frequency (Oregon State University, 1976). However, unless floristic ground surveys are systematically applied to all the boundaries, the problem remains similar to that of the MHW line and a compromise based on experience and photointerpretive skill will probably remain the most precise limit available.

Assessment of wetland value

There are no hard and fast rules for evaluating wetlands although most trade-offs involving wetland loss are based on economics. Attempts have been made to evaluate wetlands in terms of potential for agriculture or tertiary sewage treatment (Gosselink and others, 1974) but most present decisions appear to be based on species composition (for example Silberhorn and others, 1974), or on primary productivity, i.e., species composition, biomass. If species composition is to be used as a criteria for evaluation, its determination is most efficiently made during mapping or inventory.

Mapping methodology

Development of techniques should be on a wetland class or type basis. Each class has certain unique features that cause the mapping approach to differ. For example, the detection of submerged aquatic vegetation has long been a problem to wetland mappers. The problem is compounded by abundance and the tendency of submerged aquatic beds to shift position and abundance from year-to-year. The presence of high turbidity in coastal waters limits the effective water penetration of aerial photographs.

Overlapping responsibilities

A problem involved in coastal wetland inventory and management is that of overlapping federal, state and local responsibility. The National Oceanic and Atmospheric Administration (NOAA), the U.S. Army Corps of Engineers, (C. of E.), EPA, and the FWS all have varying degrees of involvement with coastal wetlands, and their responsibilities, in turn, overlap those of state and local agencies which causes an extremely complex situation for maximum protection of the nation's wetlands.

PAST RESEARCH

It would be difficult to discuss today's remote sensing methodology without alluding to the research which laid the groundwork for development of practical wetland inventory techniques. Experiments with remotely-sensed data have included the use of aircraft and satellite photographs, multispectral scanners, radar and microwave data. Research has been conducted into film/filter combinations, analogue and digital multispectral techniques, scales and formats for data presentation, and numerous other aspects of remote sensing related to coastal wetlands. Table I is a summary of selected examples of research projects into the use of aircraft sensors for coastal wetlands. Satellite experimental work is discussed later under Satellites.

Careful reading of the historical (pre-1976) literature in remote sensing of wetlands shows that coastal wetlands, especially marshes, can be mapped with black-and-white (B/W) panchromatic, B/W multispectral, natural color or color infrared (IR) photographs, and even digital multispectral scanner (MSS) data. Successful mapping depends largely on the quality and resolution of the photography or imagery, the scale of the photographs or images relative to the desired mapping scale, and the skill of the investigators. Generally, however, where species composition is important, most investigators have recommended color IR as a first choice except for submergent aquatic vegetation.

PRESENT PROGRAMS

Coastal wetland inventory and mapping are presently being conducted by both Federal and State agencies on an operational basis. B/W panchromatic photographs have traditionally been used for mapping (for example, Soil Conservation Service (SCS), USGS maps), but as a result of research mentioned above, color and color IR photographs are also being used extensively. Most state inventories are based upon aircraft photographs supplemented by ground surveys and

previously published maps, reports, and soil surveys. All 23 of the coastal states (excluding the Great Lakes states) have completed, or are presently conducting, total or partial inventories of coastal wetlands (U.S. Fish and Wildlife Service, 1976). At least 11 states completed one inventory between 1965-75; several states made more than one inventory (for example, Rhode Island, Delaware). In many states (for example, California, Washington, Florida) inventories are being or have been made by different agencies or universities utilizing different source materials, classification systems, mapping techniques, minimum mapping units (MMU), map scales, and map bases. Both state and national inventories are discussed below.

State inventories

State mapping and inventory projects are summarized in tables II-V below. Specific classification systems referenced in the tables are found in the list of references at the end of the paper. Selected examples are expanded upon to give an overview of inventory techniques.

The New England coastal states are using B/W panchromatic photographs as a basic data source (table II). The 3rd Rhode Island inventory was conducted using 1:12,000 leaves-off B/W aerial photographs (MacConnell, 1974). Maps were prepared by stereoscopic transfer to 1:24,000-scale USGS base maps. No field checking was done.

The central Atlantic states are under very heavy developmental pressures, thus the mapping has been rather detailed and new techniques are being used (table III). The greatest variety of inventory techniques have been used in this area, so several examples are discussed here. In New York and New Jersey, color IR photographs were the principal data source (Brown, 1977). In New Jersey (2) dominant wetland species, the wetland/upland boundary, and the biological MHW line were delineated on 1:2400-scale photo base maps using manual transfer techniques. In New York, a similar procedure was used to map 6 wetland categories: (1) Coastal Fresh Marsh, (2) High Marsh or Salt Meadow, (3) Intertidal Marsh, (4) Coastal Shoals, Bars, and Mudflats, (5) Formerly Connected Tidal Wetlands, and (6) Littoral Zone. Extensive field checking was done. State plane grid coordinates, a map identification number, a legend containing title, credit references, wetland species or categories and map acquisition information were included on each map for both New Jersey and New York. The maps are intended for use in issuing wetland permits and regulating wetland use and the boundaries must be defensible in court.

In Maryland (2), the primary data source for the first phase of the wetland inventory was low-altitude color photographs (Garvin and Wheeler, 1973). Only the wetland/upland boundary was delineated on the 1:2400-scale photobase map along with ownership boundaries. A second phase of the inventory was initiated to map species composition. The MHW line which forms the boundary between state and private property, is determined in the field on a case-by-case basis.

In Virginia, coastal wetland mapping was done on a county-by-county basis using field survey supplemented with photographs where available (Silberhorn, 1974). The Virginia law, unlike most other states, defines tidal wetlands as "the area between mean low water and the elevation above mean low water equal to the factor 1.5 times the mean tidal range." At least one of 40 designated "wetland plant species" must also be present. Twelve marsh community types were defined in a classification system developed specifically for this inventory (Silberhorn and others, 1974).

The southeastern Atlantic and Gulf coastal states have the most extensive coastal wetlands of any states described in this paper except Alaska (table IV). A wide variety of classification systems are being used. North Carolina and South Carolina are the two states using only low-altitude photography for inventory. Georgia, Mississippi, and Louisiana are using high-altitude photography, Alabama and Florida are using both high- and low-altitude photography and Texas is using Landsat data. Final map product scales for this area range from 1:20,000 in Georgia to 1:500,000 in Florida and MMUs vary from less than 0.4 ha in North Carolina to 16.2 ha in Florida. Florida has five wetland inventories and Louisiana has four wetland inventories in various stages of completion. In Florida, four State agencies, two Federal agencies and the University of Florida are involved in the inventory process.

Two examples of inventory methodology are Louisiana (1) and Alabama (2). Louisiana (1) is using high-altitude color IR to update and extend a published vegetative type map of the Louisiana coastal marshes (Chabreck and others, 1968). Wetland classes, Fresh, Intermediate, Brackish and Saline Marsh, are compatible with Anderson and others, 1972. Product scales will be 1:125,000 (by Parish) and 1:250,000. In Alabama (2), the Marine Environmental Sciences Consortium has inventoried all ecological habitats of coastal Alabama including all coastal wetlands up to the 50-foot contour using high-altitude color IR photographs taken at low water

levels. The classification system devised included Beach, Salt Marsh, Brackish-mixed Marsh, Salt Bush, Salt Flat, Savannah, Fresh-mixed Marsh, Swamp and Mixed Bottomland Forest. 25% field checking was done. An atlas of maps at 1:24,000- and 1:62,500-scale was produced.

Tidal marshes along the Pacific coast are generally small in comparison with those of the southeastern Atlantic and Gulf Coasts (table V), however, many miles of beaches and rocky shores are found in this area. Wetland inventories have been specifically oriented to special needs; for example, in Washington the inventories include an Oil Baseline Study, two county wetland studies and a Harbor Dredging study. As an example of inventory procedure, Washington used 1:24,000-scale color photographs taken at low tide to interpret wetland classes and boundaries manually onto USGS 7.5-minute quadrangles. Nine general habitats were identified: Rock, Sand, Mud, Mixed Coarse, Mixed Fine, Eelgrass Bed, Kelp Bed, Salt Marsh and Open Water. Nineteen "typical" sites were field checked.

National inventories

On a national basis, USGS maps coastal wetlands as a base category on the standard map series while FWS is presently inventorying coastal wetlands as part of a new National Wetland Inventory (NWI). FWS has recently developed a new classification system as the basis for the NWI, the "Interim Classification of Wetlands and Aquatic Habitats of the United States" (Cowardin and others, 1976). This system will provide a uniform basis for comparison of map and inventory products at the national, regional, and state level. The Cowardin system is a hierarchical system based primarily on vegetation, soils and water regime (Figure 1). The highest level is the Ecological System -- all coastal (tidal) wetlands fall into the Marine or Estuarine ecological systems. The second level for both systems, Ecological subsystem, is subdivided into Subtidal and Intertidal. At the class level, there are nine classes in the Estuarine system: (1) Neretic water/benthos, (2) Aquatic Bed, (3) Reef, (4) Rocky shore, (5) Beach/Bar, (6) Flat, (7) Emergent Wetland, (8) Scrub-shrub Wetland and (9) Forested Wetland. The Marine system has only six classes since all tidal wetlands with emergents, shrubs or trees are placed in the Estuarine system. There are subclasses and dominance types below the class level. Water chemistry, water regime, soil, and special modifiers are used to complete the description of wetland type. Bailey's Ecoregion system (Bailey, 1976) is used to regionalize the data by province. It should be noted that the new system includes many classes (for example, Rocky Shores and Beaches) not traditionally considered wetland, but now being mapped by some states (for example, Oregon, Washington). The following is a brief summary of recommended film types for the 9 classes.

- o Forested wetland, Scrub-shrub wetland and Emergent wetland: These three classes of vegetated wetland are best identified and mapped using color IR photographs. B/W panchromatic appears to be a good second choice for these classes. Separation into subclasses and lower levels is good with color IR; species may be identified in many cases, even with high-altitude photographs. Brown (1977) is an excellent reference for the operational use of color IR.
- o Aquatic bed: Aquatic beds include both surface and submergent vascular and macroalgal vegetation. High turbidity in some coastal areas masks the water penetration effect of both types of color and B/W film. Color film is the 1st choice for detection and mapping of submerged aquatic vegetation. Color IR is poor for detection of underwater vegetation, but excellent for surface vegetation or submerged vegetation with surface leaves (kelp). A. P. Austin and Robert Adams (written commun. 1977), after a study in British Columbia, recommend a combination of color and color IR films, at 1:10,000 scale or greater, for the inventory of the maximum number of macroalgal classes in Aquatic Beds and Rocky Shores. Water penetration film is less useful than color.
- o Rocky Shores: As suggested above, color IR appears to be the best choice for discriminating vegetation zones (mostly macroalgae) on Rocky Shores. Oblique or vertical photographs can be used - oblique photography presents special problems in geometric orientation. Where vegetation is sparse, B/W panchromatic film appears satisfactory for mapping this class.
- o Beach/Bar; Flat: These classes can be mapped with almost any film, however, color IR shows the land/water interface or tidal boundary well, as does B/W panchromatic, whereas this boundary may be difficult to interpret from color film when turbidity is high in waters adjacent to the shore.

- o Neretic water/benthos: This class appears as open water on most film. In order to separate the Aquatic Beds from the unvegetated substrates, color film is generally required. Bottom type sediments such as sand may be identified with good, low-altitude photographs.
- o Reef: Reefs are mostly subtidal and for this reason, color film is better than color IR or B/W in most cases.

The NWI is using available aerial photography to prepare wetland maps at 1:100,000 for the entire United States including Puerto Rico and the Virgin Islands. Using a new system for aerial photograph interpretation and information digitization the NWI will create a data base, in both map and computer form, in which wetlands data will be collected, interpreted, stored and reproduced (Montanari and Townsend, 1977). The MMU for this task is approximately ½ ha: the update interval is 8-10 years.

USGS publishes several series of topographic maps of the U.S. as part of its National Mapping Program (U.S. Geological Survey and National Oceanic and Atmospheric Administration, 1977). These include the standard 1:250,000-scale series covering the entire country and the 1:24,000-scale, 7.5-minute series which is incomplete. There are approximately 3,600 7.5-minute quadrangle areas in the coastal zone of the conterminous United States, Hawaii and Puerto Rico. This number includes shoreline quadrangles plus adjacent inland quadrangles.

USGS is increasing emphasis on production and revision of maps in the coastal zone to provide users with accurate and up-to-date maps for the entire zone. Because many of the 7.5-minute quadrangle areas need new mapping or revision, quick-response products such as orthophotoquads and interim revision will be provided for many coastal areas. After consultation with State and Federal agencies, a new map series at 1:100,000-scale is being produced by USGS. This series is intended to serve as an intermediate scale base map for State, regional and national projects. Research projects such as the mapping of wetlands of Doboy Sound, Georgia, 7.5-minute quadrangle (McEwen and others, 1976) help USGS assess additional capabilities for mapping specific themes in more detail than is presently shown. A cooperative program with National Ocean Survey (NOS) has resulted in a Topographic/bathymetric map series at 1:24,000, 1:100,000 and 1:250,000 scales where bathymetric data exists. This series at the 1:250,000 scale also contains the Bureau of Land Management lease block protraction diagrams including the 3-mile limit line.

Coastal wetlands are also being inventoried and mapped operationally on a national basis as part of the Land Use and Data Analysis (LUDA) program (USGS). The LUDA system Level II classes are Forested and Nonforested Wetland (Anderson and others, 1976) -- only vegetated classes are considered wetlands. High-altitude color IR photographs are the basic data source for the 1:250,000- and 1:100,000-scale map products. The MMU for this inventory is 40 acres, the recommended update period is 5 years.

Aircraft photographs are definitely the tool of the present. In spite of disagreement over film types and scales and in spite of the problem of obtaining overflights at the time and tidal stage desired, a majority of inventories presently in progress are making use of some type of aerial photographs. In light of the high resolution of new aerial films such as those used in the Skylab Earth Terrain camera, photographs from the Space Shuttle, scheduled for launch in the 1980's (Schweickart, 1975), could conceivably be used for update or monitoring at scales of 1:100,000 or possibly larger. Even if increasingly supplemented by aircraft or satellite digital data, aerial photographs will remain a major data source for the foreseeable future because of their high resolution and the versatility and economics of manual photo-interpretation versus automated digital mapping.

Satellite data

There are no documented operational wetland programs that use satellite data for mapping. Some coastal wetland classification and mapping has been done experimentally with Skylab photographs (Anderson and others, 1975; 1976; Klemas and others, 1974a; 1975) but these data are not available for the entire U.S. coastline. The use of Landsat data is generally still in the experimental phase with coastal marshes having received the most attention to date. The program closest to being operational at present is that of Texas, where present plans are to map natural vegetative associations at 1:250,000-scale for the entire state using Landsat digital data (U.S. Fish and Wildlife Service, 1976).

The potential of both Landsat images and digital data for gross mapping of coastal marshes has been demonstrated. Anderson and others (1974, 1975), and Carter and others (1973), showed that Landsat images could be used to map wetland vegetation in the Chesapeake Bay area and along the Georgia-South Carolina coast and to classify marshes by salinity type in South Carolina. Their research also showed that tidal stage affected wetland reflectance characteristics, that seasonal data were needed to identify and delineate fresh tidal marshes, and that Landsat could be used to monitor large-scale wetland alterations (dredge disposal, canal construction, road building). Reeves (1973) used unsupervised classification techniques to map marsh and water bodies of Galveston Island, Texas. Carter and Schubert (1974) demonstrated the use of Landsat digital data, field spectral reflectance measurements and a look-up table digital analysis approach to map wetland vegetation classes, mud flats and spoil at 1:20,000-scale in Chincoteague Bay, Virginia. Carter (1976) correlated area measurements from the Chincoteague study to local primary productivity figures to estimate the yearly production from this marsh. Klemas and others (1974a, 1975) used Landsat digital data to classify coastal vegetation in Delaware, achieving accuracies as high as 80% in identification of classes. Bartlett and others (1977) have currently developed a method to use field spectral measurements and atmospheric corrections in developing algorithms for Landsat classification of coastal vegetation. Butera (1976) used aircraft and satellite MSS data to determine Louisiana marsh salinity zones from indicator plant species. In Georgia, the Department of Natural Resources prepared a public education poster, "Georgia's coast, wetlands and geologic resources", with the aid of Landsat digital data.

In other studies involving coastal wetlands (Dolan and others, 1977) have used Landsat images to determine the orientation and length of shoreline segments within larger crescentic forms found along the Atlantic coastline. Faller (1977) has developed a technique to detect and measure shoreline (land-water) interfaces from Landsat classified data. The Defense Mapping Agency (DMA) Hydrographic Center is using MSS data, primarily the green band, to evaluate and update medium and small scale nautical charts (Hammack, 1977). Not only have new reefs and shoal areas been charted, but many revisions were made following the discovery of positioning errors up to 18 km. This work was initiated following the NASA/Consteau Ocean Bathymetry Experiment which proved the feasibility of satellite bathymetry in clear ocean waters (Polcyn, 1976).

Many problems remain to be solved before Landsat is considered an operational tool for use by wetland managers. The principal constraints on the use of the present Landsat MSS data for operational wetland mapping and inventory are the necessity for geometric accuracy and the need for better spatial, spectral and radiometric resolution. Management requirements and legal considerations for wetlands necessitate great accuracy in boundary placement and map scales of 1:24,000 or larger. Landsat image data meet NMAS at scales of 1:500,000 or smaller (McEwen and Schoonmaker, 1975), but Landsat digital data must be geometrically corrected to make accurate maps. The methodology for geometric correction and sampling is now fairly well established (Riffman and McKinnon, 1974; Caron and Simon, 1975; Rowan and others, 1974; Bernstein and Stierhoff, 1976), but the costs are still high and the process is time-consuming.

Spatial resolution presents a continuing problem; the useable spatial resolution of the current MSS may be less than the nominal resolution of 0.45 ha due to interaction of contrasting scene elements or boundary pixels. Dolan and others (1977) summarize the recognition of landscape elements in the coastal zone on imagery of various types and scales. In most cases, Landsat images appear to be rather poor for recognition of the landscape elements listed relative to photographic images. Many linear wetlands, for example, "fringe marshes", beaches or rocky coasts, are not easily identified with Landsat. Other wetlands are a conglomeration of highly interspersed wetland types and the average signature within a pixel may not be at all representative of any wetland type. It has been clearly demonstrated that Landsat data are useful and reliable for spectral discrimination of large, vegetated coastal marshes, but further research and perhaps new spectral bandwidths are needed to provide spectral parameters for detailed classification of both vegetated and non-vegetated wetland types. The desirable Landsat nominal spatial resolution for direct interface with regional, national, and State inventories would appear to be approximately $\frac{1}{4}$ ha or less.

FUTURE USE OF REMOTELY-SENSED DATA

We have seen that operational wetland inventories are being conducted by State and Federal agencies, universities, and other interested groups and that these inventories and the accompanying maps supply information at all levels of detail from the simple to the complex. There is no reason to believe that management needs in the coastal zone will become any less detailed or specific in the future nor is there reason to believe that special purpose inventories will cease to be necessary. Legislation for areas of "critical environmental concern"

or endangered species habitat, for example, may necessitate new inventories. It is probable, however, that if the NWI is successfully performed to the level of detail presently anticipated, that the inventory products will supply a commonality of definition and classification and give a better understanding of the national picture. Continuing research may find solutions to the problems that still confront us, i.e., the mapping of tidal datum planes, the detection and mapping of submerged vegetation in turbid coastal areas, and the realistic evaluation of the coastal wetland resource.

Landsat digital data appear to be a powerful tool with which to update the present inventories, monitor wetlands, human impact and vegetative trends, and possibly to use on an operational basis for inventory in Alaska where available map coverage is 1:63,360-scale and smaller and the area is vast. However, in order to provide satellite-derived wetland boundaries and classes with sufficient resolution to interface directly with, and update inventories, at the national, regional, or State level, the nominal spatial resolution must be increased and geometric correction of digital data must be made economical.

Many of the problems inherent in data from Landsat 1 and 2 may be solved by new data processing methodology and technological improvements to Landsat C and D (Billingsley and others, 1976). Landsat C will have a MSS like that in Landsat 1 and 2, but a thermal band, 10.40-12.6 μm , with a resolution of 234 m will be added. The Landsat C Return Beam Vidicon (RBV) will have two individual cameras that operate in the same spectral band, 0.505 to 0.750 μm . The resolution will be 90 line pairs/mm and each camera will review a 98 km square ground scene. The Thematic Mapper (TM) of Landsat D will have six spectral bands: 0.45 to 0.52 μm , 0.52 to 0.60 μm , 0.63-0.69 μm , 0.76-0.90 μm , 1.55 to 1.75 μm , and 10.40 to 12.50 μm . The resolution of bands 1-5 will be 30 m, the resolution of band 6 (thermal) will be 120 m. The dynamic range will be raised to 256 quantification levels.

The increased number of spectral bands and the improvement of ground resolution to 30 m (approximately 0.12 ha) should improve the capability to map and inventory wetlands according to present legislative requirements. These maps will not have boundaries accurate enough for use as the basis for litigation or for conducting regulatory functions. However, improvement should be seen in separation of different wetland types once spectral and seasonal variables and combinations of bands and seasons are established through further research. Present indications are that data from at least 2, and possibly 3 or 4 dates, will be needed to identify all wetland types and to determine hydrologic/vegetative boundaries. Increased dynamic range of the sensor will allow finer radiometric classification and therefore increase the probability of separation and accurate classification of wetlands with closely similar spectral signatures.

Ultimately, efficient methods must be devised to extract information on a relatively routine basis. Improvement in data systems, data interpretation and data processing is extremely desirable. The anticipated quantity of data from Landsat D foreshadows the urgent need in this area. Small individual wetland inventories (county, even State) could be accomplished with present methodology and the improved resolution, but the problems of extraction of nationwide wetland information needs additional attention. Present attempts at regional or State mapping are being concentrated on overall land use and land cover and will not provide the more detailed wetland classification needed to accomplish a national inventory.

Until research on satellite methodology is farther along, aircraft data will still be needed to check accuracy, evaluate analysis results, and provide products of the high resolution and accuracy required for ongoing operational programs. Demands for auxiliary aircraft coverage should not be excessive, provided the data exists for the correct season(s). However, additional aircraft coverage may be required where detailed ongoing monitoring is necessary.

Finally, it should be recognized that satellite data have great potential for global wetland inventory where very little information exists. Two programs having potential use for such data are the Man and the Biosphere (MAB) program and the International Conservation of Nature and Natural Resources (ICNU) program on wetlands.

SUMMARY AND CONCLUSIONS

This paper has presented an overview of the applications of remotely-sensed data to coastal wetlands. Technical problems include (1) definition and classification; (2) scale, formats and boundaries; (3) evaluation, (4) submerged aquatic plants, and (5) overlapping responsibilities. Today's operational inventories in coastal states are built on the past decade of research and technology development in remote sensing of wetlands. These inventories and map products

utilize aerial photographs as a basic data source and differ in scale, format, MMU, classification system and purpose. The FWS is conducting a new national inventory of wetlands which is intended to provide a standardized basis for comparison of wetlands - it too will use available aerial photographs as a basic data source.

In the future, satellite data may provide an accurate, reliable and economical source to update wetland inventories and to monitor or evaluate coastal wetlands. The improvement in technology accompanying the development and launch of Landsat C and D and the Space Shuttle promise to make satellite digital data a more powerful tool to supply future management needs for coastal wetlands.

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TABLE I: Selected research projects in remote sensing of coastal wetlands

Authors	Type of Study	Data Source	Conclusions
Cameron (1950)	Seaweed survey	low-altitude filtered B/W panchromatic, color	Aerial photography a rapid method to survey seaweed to 4 fathoms depth. Color is superior to B/W. Two species can be differentiated.
Olson (1964)	Tidal fresh marsh vegetation studies	low-altitude black-and-white (B/W) panchromatic, color and color negative	General types of marsh vegetation, broad ecological zones, and many plant species and associations can be recognized. There are little differences in accuracy between the three types of photographs.
Stroud and Cooper (1968)	Tidal salt marsh vegetation and primary productivity	low-altitude color and color IR	Acreages of community types may be determined with color IR. Estimates of primary productivity can be made.
Pestrong (1969)	Tidal salt marsh vegetation and geomorphology	low-altitude multiband photographs, color, color IR and B/W panchromatic	Color IR best for vegetation discrimination.
Anderson (1969)	Tidal fresh and brackish marsh vegetation	low-altitude color IR from June and September, thermal IR	Color IR superior to color for marshland plant delineation, especially with increase in altitude. Thermal infrared can be used to identify certain species. Seasonal changes in vegetation affect interpretation.
Kelly and Conrad (1969)	Shallow water benthic communities	low-altitude color, B/W photographs, satellite photographs	Location, depth, and quantitative characteristics of bottom biota, sediments, and morphology identified. Density of algae and sea grass can be estimated.
Carter and Anderson (1972)	Tidal marsh spectral reflectance	low-altitude color IR high-altitude color IR spectral reflectance measurements	Spectral reflectance differences between marsh plants depend on density, leaf orientation, back-ground water or soil, and sediment deposited on leaves.
Cibula (1972)	Fresh to brackish tidal marsh vegetation	aircraft multispectral scanner	Classification of plant communities possible with automatic pattern recognition techniques and limited ground calibration.

Table I: continued

Authors	Type of Study	Data Source	Conclusions
Guss (1972)	Tidal salt marsh vegetation and tidal boundaries	low-altitude color, color IR and multispectral photographs	Color-combined multispectral photography recommended to differentiate species and to locate MHW line.
Reimold and others (1973)	Tidal salt marsh vegetation and primary productivity	low-altitude color IR, thermal imagery	Color IR increases accuracy of primary productivity estimates for large marsh areas.
Anderson and Wobber (1973)	Tidal marsh vegetation and boundaries	low-altitude color IR and color	Pilot study shows biological discrimination techniques can be applied to operational wetland species and boundary mapping.
Klemas and others (1974b)	Tidal marsh vegetative communities	high-altitude color IR	Delaware's coastal wetlands inventoried using manual interpretation and multispectral analysis.
McEwen and others (1976)	Tidal marsh boundaries and species	high-altitude color IR	Vegetation interpretation practical, economic and accurate for establishing upper wetland boundary within NMAS. Interpretations were made from color IR to orthophoto base.
Shima and others (1976)	Tidal fresh marsh	low-altitude color IR	Low-altitude color IR good for mapping fresh-water marshes if season is considered and systematic field checking is done. Extrapolation from one area to another is difficult.
Martin (1975)	Tidal marsh map products	high-altitude multispectral B/W	Color orthophotoquads may permit direct interpretation of coastal features without transfer of interpreted data from photographs to orthophoto base.

TABLE II: Wetland inventories of the New England coastal states.

* I = not completed, P = partial coverage, C = completed. Where more than one inventory exists, inventories are numbered.

State	Inventory Status	Data Source	MMU	Product Scale	Classification System
Maine	I	low-altitude B/W panchromatic	2 ha 0.4 ha	1:48,000 1:24,000	SCS Soil type and Maine land cover system
New Hampshire	P	low-altitude B/W panchromatic	0.8 ha	1:24,000	SCS soil type
Massachusetts	C	low-altitude B/W panchromatic	15 ha	1:24,000	modified Martin and others (1953)
Rhode Island (1) salt marsh inventory	C	low-altitude B/W panchromatic	5 m (width)	1:12,000	species listed in existing laws.
(2) wetland inventory	C	low-altitude B/W panchromatic	0.4 ha	1:12,000	project specific
(3) map-down	C	low-altitude B/W panchromatic	1.2 ha	1:24,000	modified Martin and others (1953)
Connecticut	I	low-altitude B/W panchromatic	---	1:24,000	species listed in existing laws.

* Information from U.S. Fish and Wildlife Service (1976)

TABLE III: Wetland inventories of the central Atlantic states.
 * I = incomplete, C = completed, P = partial. Where more than one inventory exists, the inventories are numbered.

State	Inventory Status	Data Source	MMU	Product Scale	Classification System
New York	I	low-altitude B/W panchromatic, color IR	0.2 ha	1:24,000	combined Martin and others (1953) and Golet and Larson (1974)
New Jersey	I	low-altitude color IR	0.04 ha	1:2400	dominant vegetation
(1) Tidelands delineation					
(2) Coastal wetlands inventory	C	low-altitude color IR	2 ha	1:2400	species in law
(3) Delaware River estuarine marsh survey	CP	field survey, low-altitude B/W panchromatic	wider than 200 ft.	1:24,000	dominant vegetation
(4) Wetland ecology marsh destruction	C	field survey	0.4 ha	1:24,000	loss categories - filling, diking
Delaware	I	low-altitude B/W panchromatic, color, and color IR	2 ha	1:24,000	project specific
(1) Wetlands Atlas					
(2) State wet- lands inventory	C	low-altitude color, color IR and B/W panchro- matic	1.6 ha	1:24,000	species listed in existing law.

* Information from U.S. Fish and Wildlife Service (1976)

TABLE III: continued

State	Inventory Status	Data Source	MMU	Product Scale	Classification System
(3) Delaware River estuarine marsh survey	C	high-altitude color IR	200 ft.	1:24,000	dominant vegetation
Maryland (1) Coastal wetland inventory	I	low-altitude B/W panchromatic color, and color IR	0.1 ha	1:2400	dominant vegetation
(2) Wetland habitat inventory	C	field survey	2 ha	1:63,360	modified Martin and others (1953)
Virginia	C	field survey, supplemental with low-altitude color IR or B/W panchromatic if available	0.10 ha	1:24,000	dominant vegetation

TABLE IV: Wetland inventories of the southern Atlantic and Gulf coast states.
 * I = incomplete, C = complete, P = partial. Where more than one inventory exists, inventories are numbered.

State	Inventory Status	Data Source	MMU	Product Scale	Classification System
North Carolina	I	low-altitude B/W panchromatic	less than 0.4 ha	1:24,000	tidal marshlands
South Carolina	C	low-altitude B/W panchromatic, color IR	0.4 ha	1:24,000	project specific
Georgia	I	high-altitude color IR, soil survey reports	1.2 ha 4 ha	1:20,000 1:24,000	Martin and others (1953)
Florida (1) Carrying capacity for man and nature in South Florida	IP	high-altitude color IR and B/W IR, soils, maps, previous publications	4 ha	1:77,116, 1:250,000, 1:154,000, 1:500,000	gross metabolism - project specific
(2) Forested wetlands	IP	high-altitude B/W IR	4 ha	1:80,000, 1:500,000	forested wetlands - project specific
(3) Northeast Gulf River Basins	IP	low-altitude B/W panchromatic	10 ha	1:24,000	project specific
(4) Central and Southern Florida Control District	CP	low-altitude B/W panchromatic	4 ha	1:500,000	wetlands

* Information from U.S. Fish and Wildlife Service (1976)

TABLE IV: continued

State	Inventory Status	Data Source	MMU	Product Scale	Classification System
(5) Coastal zone management atlas	IP	low-altitude B/W panchromatic	0.8 ha	1:24,000	project specific + vegetation and soils
	C	low-altitude B/W panchromatic, high-altitude color infrared	16.2 ha		modified Anderson and others (1972)
Mississippi (1) Photomaps of coastal wetlands	C	high-altitude color IR	0.4 ha	1:24,000	wetlands
(2) Marshes	CP	field survey	---	1:62,500	Penfound and Hathaway (1938)
Alabama (1) coastal wetlands	C	low-altitude B/W panchromatic, some color IR	0.4 ha	1:24,000	vegetation, biological MHW
(2) Coastal ecological habitats	C	high-altitude color IR	0.4 ha	1:24,000 1:62,500	vegetation - project specific
Louisiana (1) Coastal resources program	I	high-altitude color IR published vegetation map	10 ha	1:125,000 1:250,000	Anderson and others (1972)
(2) Inventory of basic environmental data	CP	high-altitude color IR	---	1:125,000 1:250,000	Penfound and Hathaway (1938)

TABLE IV: continued

State	Inventory Status	Data Source	MMU	Product Scale	Classification System
(3) Inventory of basic environmental data	CP	high-altitude color and color RI, Landsat	---	1:250,000 1:633,600	vegetation and salinity
(4) Vegetation, water and soil of Louisiana coast	C	field survey	---	1:380,000	project specific
Texas (1) Habitat type mapping	C	aerial photos previous publications	---	1:125,000 1:250,000	environmental geologic units
(2) Environmental geologic atlas of the coastal zone	I	Landsat	16 ha	1:250,000	natural vegetation associations

TABLE V: Wetland inventories of the Pacific coast states.
 * I = incomplete, C = complete, P = partial. Where more than one inventory exists, inventories are numbered.

State	Inventory Status	Data Source	MMU	Product Scale	Classification System
California					
(1) Wetland studies	IP	previous publications low-altitude B/W panchromatic	varies	1:12,000 to 1:120,000	varies from report-to-report
(2) Coastal plain	C	previous publications low-altitude B/W panchromatic color	8.1 ha	1:62,500	Wetland or Estuary
(3) North coastal region	CP	low-altitude color, high-altitude and low-altitude color IR	---	1:24,000	identified only
(4) South San Francisco Bay	CP	field survey previous publication	100x100 ft.	1:24,000 1:2400	project specific
(5) Suisun marsh	CP	low-altitude color		1:24,000	vegetation
Oregon					
(1) Coastal conservation and Development Commission	C	high- and low-altitude aerial photographs previous publications	less than 0.4 ha to 258 ha	1:12,800 to 1:250,000	varies from report-to-report - coastal zone classes
(2) Estuaries	C	low-altitude B/W panchromatic	---	1:12,000 1:24,000	estuary study

* Information from U.S. Fish and Wildlife Service (1976)

TABLE V: continued

State	Inventory Status	Data Source	MMU	Product Scale	Classification System
Washington	I	low-altitude color	---	1:24,000	9 habitat types
(1) Oil base-line study					
(2) Skagit County wetlands	CP	high-altitude color IR, color			project specific
		low-altitude color IR, color, B/W panchromatic	0.4 ha	1:24,000	modified Martin and others (1953)
(3) Gray's harbor dredging study	CP	low-altitude color IR	---	1:40,000	project specific
(4) Jefferson County	CP	low-altitude B/W panchromatic	---	1:12,000 1:4800	Akins and Jefferson (1973)
Alaska	I		-- in planning stages --		
Hawaii	I		-- in planning stages --		

* Information from U.S. Fish and Wildlife Service (1976)

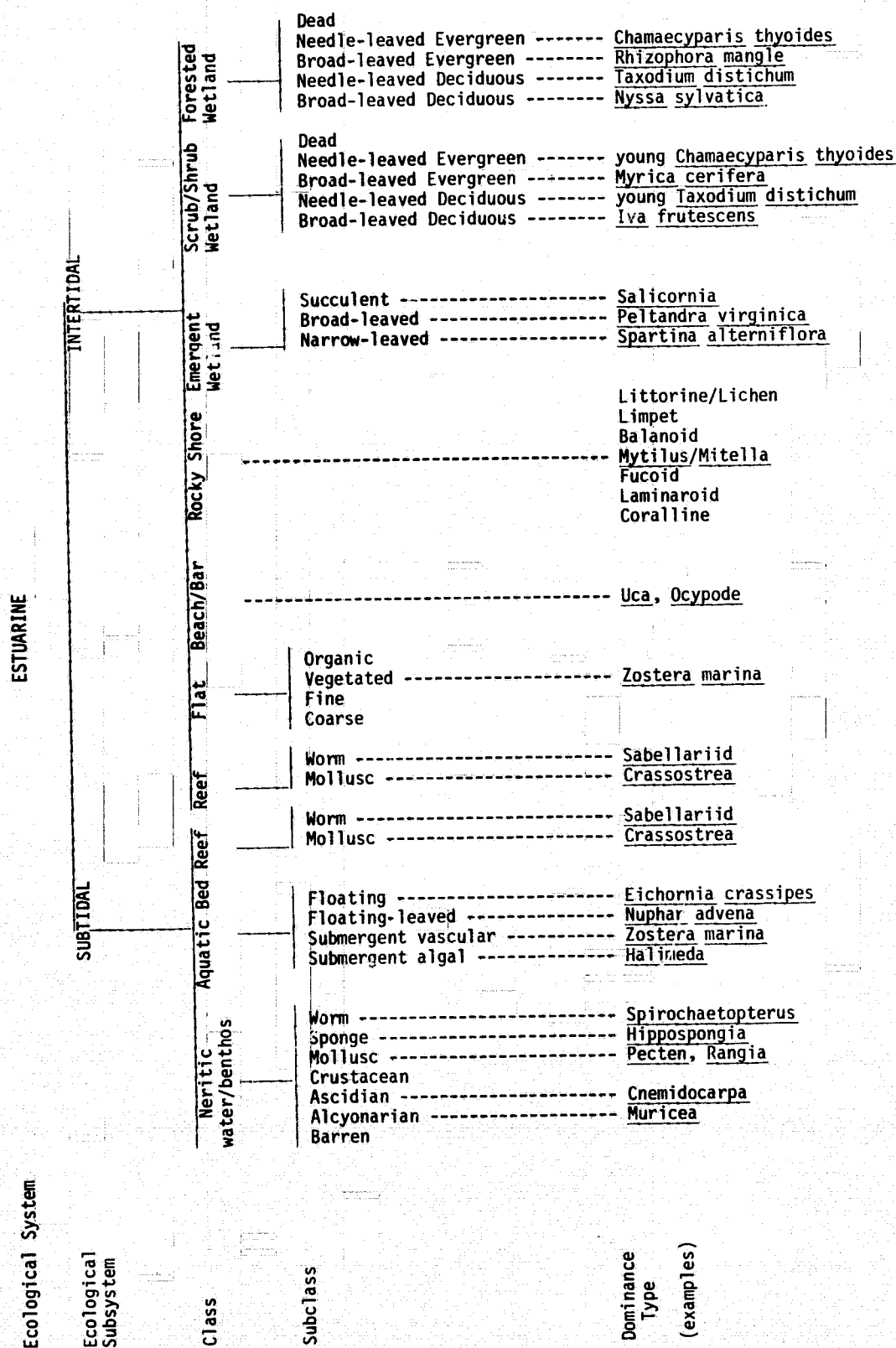


Figure 2. Diagram of the classification hierarchy for the estuarine ecological system. (modified from Cowardin and others, 1976)

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AN OVERVIEW OF REMOTE SENSING TECHNOLOGY TRANSFER
IN CANADA AND THE UNITED STATES

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ABSTRACT

To realize the maximum potential benefits of remote sensing, the technology must be applied by personnel responsible for the management of natural resources and the environment. In Canada and the United States, these managers are often in local offices and are not those responsible for the development of systems to acquire, preprocess, and disseminate remotely sensed data, nor those leading the research and development of techniques for analysis of the data. However, the latter organizations have recognized that the technology they develop must be transferred to the management agencies if the technology is to be useful to society. Problems of motivation and communication associated with the technology transfer process, and some of the methods employed by Federal, State, Provincial, and local agencies, academic institutions, and private organizations to overcome these problems are explored.

1. INTRODUCTION

The process of technology transfer in any field is complex. Normally, research results require decades to achieve practical application. According to a recent study by Battelle Columbus Laboratories, technologically advanced societies are unable to quickly transform new ideas into successful products. Time from the first year of conception to the first year of realization for the heart pacemaker, hybrid corn, and the oral contraceptive was 32 years, 25 years, and 9 years, respectively. Battelle study indicated the time required to develop 10 innovations was 19.2 years.

In North America, conscientious efforts are being made within government agencies and some academic institutions to shorten the time leading to the application of the technology of remote sensing. Many methods are being explored, including the use of conferences, seminars, short courses, workshops, lectures, information packets, newsletters, films, slide sets, teaching modules, technical reports and other publications, and on-the-job training in joint projects. Common to all of these methods is some form of training for prospective users of the technology, backed by ongoing research into new methods of meeting the information-gathering needs of resource and environment managers.

A communication problem is inherent in the establishment of an understanding between the remote-sensing technologists (i.e., research and development personnel) and the resource and environmental managers, who work on different kinds of problems, use different approaches to their solution, and operate under different political and administrative pressures. Often a strong resistance exists on the part of the user to apply new techniques to a task that he now performs in some well established, traditional manner. Experience has shown that each approach to overcoming these inherent problems in technology transfer must be geared towards creating awareness, instilling maximum credibility, and producing positive payoffs for the manager. Research results must be repackaged into more understandable forms which involve the user

through access to specialized equipment and opportunities for "hands-on" training.

PROBLEMS IN TECHNOLOGY TRANSFER

The problems associated with transferring remote-sensing technology to user agencies, i.e., those entrusted with making the final management decisions with respect to resources and environment, are complex. These problems are similar to those involved in any technology transfer process and may be broken down to two broad categories: motivation and communication.

Motivation

Before any attempt can be made to transfer a new technology to a prospective user, he must be motivated to accept it. Thus, it is useful to examine some of the factors which might mitigate against such acceptance. Downs (1967) studied the difficulties associated with effective utilization of digital computers in "urban information systems". Those engaged in efforts to transfer remote-sensing technology will recognize the same sources of resistance.

New technical developments may be viewed with skepticism or at best uncertainty and uneasiness by the key decision makers. It is usually difficult to judge whether the new approaches are really worth the cost. Often the new technology appears overly complex to the manager because he seeks simple solutions to his problems. More important, perhaps, is the question as to how the information gathered with the aid of the new technology will affect the power and influence of the individuals engaged in the decision-making processes. The final payoffs of the use of remote sensing in a particular situation will be determined by actual improvements in job performance, or by actual cost reductions in information gathering.

Improved job efficiency, productivity, or a reduction in costs as a result of using remote-sensing technology are very important. Ultimately, however, for a decision-maker to be won over by the technology, "he must perceive a net gain in his decision-making effectiveness, and hence power, at the expense of another person's" (Downs, 1967). He is not likely to admit this publicly, or perhaps even to himself! Thus, to tell a manager that he will be able to reduce his budget and drastically cut his staff through effective use of remote sensing may actually have a negative effect on his view of the subject, for he may perceive his power in terms of his budget and staff. On the other hand, the person in a position to redirect the saved resources may indeed see advantages in the application of the new technology.

Other important factors working against adoption of new procedures are the practical difficulty in experimenting with a new system and the danger that the new system may not effectively reduce costs or increase production. Generally, any decision-maker has a system for gathering the information he needs to do his management tasks. Normally tight limits exist on the financial and other resources at his disposal. Implementation of a new technique usually requires diversion of already limited resources in a gamble that the new approach may be more effective. To the resource or environment manager, this gamble can be dangerous. He normally doesn't have the resources to attempt a parallel operation using the new method as well as the traditional one. Moreover, his existing staff will likely possess different, possibly lower, skills than those required to exercise the new techniques. He knows how to do his job with current resources, but he isn't certain that the new technology will enable him to get his job done at the same or lower costs. Because he doesn't have excess resources to enable him to experiment, he cannot afford to take the risk of failing to meet his goals in cost-effectiveness on the off-chance that he might exceed them with the aid of remote sensing.

Lastly, the resource manager must gain the confidence of his own upper management when implementing changes. Consequently, he must not only understand the new technology and its associated risks, but must also be articulate on the subject before his superiors to gain their support.

Communication

While the problems of communication may be just as difficult as the motivational ones, they tend to be better understood. Because of natural inclinations, formal training, and work experience, technologists are used to solving different kinds of problems, using different approaches, and operating under different pressures; they even have a different "language" than the resource and environment managers. The technologist is usually an engineer, mathematician or physicist by training. He generally has a strong background in mathematics and physics, and is skilled at working with computers and other machinery. The technologist is accustomed to precise formulation of problems that can be solved by the application of a logical series of strict and unalterable rules and procedures. He often revels in complexity, provided that it can be broken down into simple, completely logical sub elements. Generally, the technologist's work is in the form of "feasibility analysis" performed in an atypical research environment. Often he is overly optimistic about the practical utility of his results and frequently presents his results to his own peer group of technologists, rather than to the potential users of the technology. In addition, he has his own jargon to express the problems and their solution, but this language may be unintelligible to the uninitiated.

The resource or environment manager may have less formal education than the technologist, at least in physics and mathematics, which are the foundations for the intelligent acquisition and analysis of remotely sensed data. The education of the manager is usually in the life, Earth, or environmental sciences. He may abhor, or at least mistrust, computers and other "machines". Many of his problems are even more complex than those of the technologist and do not lend themselves to neat, precise, and logical compartmentalization. They must be solved using subjective judgment based upon experience more than the application of straight forward rules and procedures. Because of the manager's experience and background, he may find it impossible to express his problems in the precise manner desired by the technologist, even when these problems are amenable to precise expression. The manager, too, has his own jargon.

TACKLING THE MOTIVATION PROBLEMS

During this discussion of the manager's resistance to the adoption of a new technology, the picture may have seemed quite bleak. However, it must be remembered that not all resource and environment managers resist change, and the factors cited merely help to explain resistance when it is encountered. Many managers are excited by new ideas and concepts and are willing to take risks in adopting new methods. Sometimes the benefits of using remote sensing are so obvious that the decision maker realizes almost immediately that it is to his advantage to incorporate the techniques into his information gathering system. To a very large extent, those engaged in remote-sensing technology methods and who have the resources to try them. Indeed, in many cases it has been the resource or environment managers who have actively sought the assistance of the technologist!

Although "cost-benefit" studies (e.g., Clough, 1975) are generally designed to justify the application of the technology itself, they are also used to convince users of the value of remote sensing. However, the ability of traditional cost-benefit studies to facilitate user acceptance remains to be demonstrated. On the contrary, evidence suggests that potential users are likely to regard independently-performed evaluations with extreme skepticism and occasionally with hostility (Sharp, 1977). Dubious assumptions imbedded in analytical models often obscure the problems and decision processes of real-life managers. From the standpoint of the developers of remote-sensing technology, the consequences of a lack of realistic assumptions in even the more tidy analyses are that the fruits of the new technology are not really worth their price. Even when the studies are well performed, use credible assumptions, and are done in full cooperation with the user, the cost-benefit figures derived are too often taken out of context. Usually the benefits are increased productivity or monetary savings, neither of which can be properly measured. Thus, after remote sensing is adopted, the agencies controlling the money are disappointed

because the benefits can rarely be measured in terms of budget or staff cuts.

To overcome the natural resistance to adoption of remote-sensing technology, the agency transferring the technology must continually seek out those managers who are receptive to change. As more "success stories" are written or told, more of the conservative managers will see the benefits to be achieved by remote-sensing and will gradually become convinced that they too must take advantage of the new management tools. Those engaged in the technology-transfer process must be aware of the "power payoffs" that are so important, even if only subconsciously so, provide the essential motivation to the manager. This may mean seeking out the correct person in the organizational structure; the one who will definitely see the power gain to be achieved by himself. The technology serves flesh-and-blood managers who sorely need the help of remote-sensing systems, but who will not accept or effectively use such help unless it serves their own interests.

TACKLING THE COMMUNICATION PROBLEMS

Training and education are the accepted and successful approaches to tackling communications problems in transferring remote-sensing technology to the resource and environment managers. Education may be accomplished at the university level by courses in the environmental sciences, or through complete programs concentrating on the application of remote sensing, particularly at the graduate level. In 1975, there were at least 470 courses in the United States and 64 in Canada that stressed remote sensing (Nealey, 1977). Many agencies, including universities, offer short-courses of 1- to 4-week duration. These range from elementary introductory courses covering a broad range of disciplines to highly specialized training sessions geared to the needs to users in specialized areas of management. Among the universities offering this type of short-course training are the University of Arizona, University of California, George Washington University, University of Idaho, University of Kansas, University of Michigan, University of New Mexico, Purdue University, Oregon State University, South Dakota State University, and Texas A & M University.

Scientists traditionally communicate new techniques and research results by the publication of technical papers and reports and by presentations at conferences and symposia. These methods of information exchange are suitable for communication between the remote-sensing technologist and the resource-manager scientist. It is incumbent upon both the technologist and resource-manager scientist to translate these research results into practical applications. This translation can work quite effectively in organizations which contain both research and operating branches, or in operating agencies that depend upon a research agency to provide new techniques and methods.

An important adjunct to the training programs of agencies engaged in the transfer of remote-sensing technology is the preparation of complete, yet concise, training-aid material. This material is normally developed by an agency to improve its own efficiency in conducting training sessions. However, if the material is well prepared, it can be used by other organizations engaged in technology transfer, or even by the management agencies themselves. Such aids may include films, slide sets, video tapes, printed course material including exercises and workshop material, and teaching modules. Among such training aids currently available is the minicourse series on the fundamentals of remote sensing available from Purdue University (Lindenlaub, David, and Morrison, 1974). This series of self-instructional units consists of a set of slides, an audio-tape, and a study guide for each minicourse. Widely distributed newsletters serve to keep users abreast of some of the latest developments in the application of remote sensing to management problems. Complete documentation of successful approaches used during the execution of pilot or demonstration projects can be employed to generate information packets or case studies that in turn may be used by managers directing work in the same or similar fields.

In addition to offering formal training, most non-academic agencies engaged in the transfer of remote-sensing technology provide assistance to users through informal consultation services. Such consultation may consist of hosting visiting scientists and managers, answering telephone inquiries, or

presenting lectures. Some agencies operate libraries that maintain and update collections of remote-sensing literature and information and provide reference assistance to users in the form of computerized storage and retrieval of reference citations.

The education and training methods described above are ideally suited to introducing the new or prospective user of remote-sensing techniques to the subject or for providing occasional assistance to the well established user. Experience has shown that one of the most effective methods of accomplishing the transfer of remote-sensing technology is through demonstration or pilot projects. These projects may take two forms: The most common, and often least effective, form is used when the technical agency is unable to find an interested management agency; nevertheless, the technical agency is convinced that remote sensing could and should be used to solve a particular problem. In this case, the technology-oriented group, augmented by scientists and engineers familiar with resources and environmental problems, will perform a demonstration experiment that documents the results and benefits to be achieved. The documentation is then presented to potential operational users as an example, and they are encouraged to adopt the procedures. The danger in this approach is that the user, not being directly involved, may feel that the new idea is being thrust upon him and therefore may remain skeptical and reject the proposal for any variety of reasons. The proposal may be rejected because the proposer has failed to take into account some not-so-obvious factor that is important to the resource or environment manager. Or perhaps resentment may drive the manager to grasp for even flimsy excuses to avoid adoption of the new techniques.

Many organizations that transfer remote-sensing technology follow a policy of conducting demonstration projects only in cooperation with a user agency. In this way, the user is fully involved from the outset, and can identify even obscure problems as the techniques are demonstrated. Furthermore, through his commitment to take part in the demonstration, he has demonstrated that he is motivated to give the techniques a fair trial. Because he has devoted some of his own resources to the project, he becomes committed to its success. A common approach adopted by agencies transferring remote-sensing technology is to have an user agency, be it Federal, State, Provincial, municipal, or private industry, actually perform the work. The technical agency will provide technical assistance, training, and in some cases access to equipment and facilities. Each project is designed to demonstrate the utility of remote-sensing technology for solving resource-survey, inventory, or monitoring problems. The procedures for utilizing the remote-sensing techniques are usually documented, published, and disseminated. Usually, these projects are designed for a specific user agency responsible for only one management area. However, a few very ambitious projects have been undertaken to incorporate remote-sensing techniques throughout the whole State government resource and environment management structure.

One such project being conducted by 35 state agencies, regional councils and local units of government includes about 80 resource and environmental managers in the states of Oregon, Washington, and Idaho (Hedrick, Cunningham, Shay, Lake, and McCormick, 1976). Work is underway in the inventory of agricultural, forest, and range lands and in the study and mapping of urban land use. Each remote-sensing demonstration is completely "user driven" and tailored to meet the specific needs of the agencies in the three states. Not only have the agency personnel actually used remote sensing, but their central computer specialists have been assisted in the specification, acquisition, and integration of computer-based analysis systems. Agencies have also been assisted in the procurement of sensor and recording equipment for airborne data-acquisition systems.

In Canada, the Canadian Centre of Remote Sensing, Ottawa, Ontario, and the Alberta Remote Sensing Program, Edmonton, Alberta, are the most active organizations conducting technology transfer. Similarly, in the United States, NASA's Goddard Space Flight Center, Greenbelt, Maryland; Earth Resources Laboratory, Slidell, Louisiana; Ames Research Center, Sunnyvale, California. The U.S. Geological Survey's Earth Resources Observation Systems Data Center, Sioux Falls, South Dakota, are conducting programs that focus on the transfer of remote-sensing technology.

ORIGINAL PAGE IS
OF POOR QUALITY

Most of the industrial organizations that manufacture equipment used for the analysis of remotely sensed data also provide useful technology transfer services. These organizations provide user assistance, training, and access to equipment. The organizations engage in joint projects with user agencies who have demonstrated their commitment to the work by their willingness to pay for assistance.

The key concept in all of these approaches to training the users is utilization of a team containing both research and development specialists and resource specialists. By working together both on a long-term and on a daily basis, the communication problems are overcome. During many projects, the remote-sensing technologists are able to continue their research into the development of new methods of acquiring and analysing remotely sensed data. Because the technologist is in daily contact with the discipline-oriented scientist, they are not isolated from each other as is usually the case. They learn each other's jargon, and gradually come to understand each other's difficulties. In this way, user problems are more easily expressed to the technologist, who is able to explain the technology in terms that can be understood by the user. Despite this progress, the technology developers must concentrate more on providing simple, easy-to-use solutions rather than on esoteric, incomprehensible ones.

SUMMARY AND CONCLUSIONS

As more operating agencies succeed in applying the tools of remote sensing to their daily management problems, the reluctance of others to try this relatively new technology hopefully will decrease. This success will result in an increasing need for those who already have the knowledge and capability to provide more effective education, training and assistance to the user. Today, the remote-sensing technologists are under increasing pressure to demonstrate the value of this technology to society. Thus, it will become more important to document the benefits achieved through this technology, even if they are intangible. The need for this documentation should be stressed in all forms of training.

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TECHNICAL ASSISTANCE
AND THE TRANSFER OF
REMOTE SENSING TECHNOLOGY

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ABSTRACT

The transfer of technology from industrialized countries to the third world is a very complicated process and one that requires a great deal of research and development. The political and social obstacles to this transfer are generally greater than the technical obstacles, but technical assistance programs have neither the competence nor the inclination to deal with these factors adequately. Funding for technical assistance in remote sensing is now expanding rapidly, and there is a growing need for institutions to study and promote the effective use of this technology for economic development. The United Nations, the Food and Agriculture Organization, the World Bank, the United States Agency for International Development and the Canadian technical assistance agencies take different approaches to the problem and deal with the political pressures in different ways.

I. THE NATURE OF TECHNICAL ASSISTANCE

The transfer of technology from research and development to operational institutions within industrialized countries is a slow and difficult process since the gap between the research scientist and the operational program manager is large. The gap between the research scientist in an industrialized country and the program manager in the third world is very much greater, and the transfer of technology is slower and more difficult. In addition to the difficulties of communication and motivation which exist in industrialized countries (Strome and Lauer, 1977), there are greater difficulties presented by cultural, political and economic differences.

In spite of these often overwhelming obstacles, there is a strong tendency for international technical assistance agencies to assume that the transfer of technology to the third world is straightforward and can achieve fast results. There is a pressure to fund large scale operational projects which are expected to produce substantial economic benefits in a short time rather than to fund research and development projects designed to increase understanding of the problems involved. As a result, the process of international transfer of technology is very poorly understood and little progress is being made to improve the situation.

The problems of technical assistance require long and intensive research before good results can be reliably expected. Projects should have extensive preparatory research and, even more important, intensive critical evaluation of the results including an analysis of the political and social factors involved. The lack of critical evaluation in technical assistance programs is an almost inevitable result of the political nature of such programs and is therefore not an easy obstacle to overcome. An understanding of the forces which inhibit this critical approach requires an analysis of the mechanism of technical assistance and the political forces involved.

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A technical assistance program (Fig. 1) consists of money, supplied by taxpayers in an industrialized country, being used to provide experts and materials to a third world government to provide services to the people.

The taxpayers who provide the money do not expect to receive any benefits from the program and are therefore not particularly concerned with how the money is used or whether it achieves the intended results. In domestic government spending programs, by contrast, the taxpayers expect to receive benefits and will critically weigh the costs and benefits.

The technical assistance agency that spends the money is judged internationally on the basis of how much money it spends, not on how effectively it spends it. Accordingly, the amount of money provided is determined by political criteria rather than by the results or the need. Whereas domestic government programs must justify their existence and compete for funds on the basis of economic and social results, technical assistance programs are rarely called upon to produce cost-benefit studies.

Assistance is provided primarily in the form of experts and materials from the donor country and is always provided to or through the government of the recipient country. Since third world countries are generally culturally heterogeneous and economically and politically unstable, the first priority of the government is to consolidate central authority. Offers of assistance will rarely be turned down since they contribute to the power and prestige of the central authorities regardless of how they are applied. The recipient government is not inclined to offer any criticism which might inhibit the generosity of the donor.

The final element of the system, the people of the third world country, have very little voice in the whole process. Third world governments are almost all authoritarian, and the gap between those in power and the largely rural and illiterate people is large. The press, which is an important source of critical review in western industrialized countries, is government controlled in most of the third world and cannot serve this function.

The above analysis of the mechanisms of technical assistance shows why such programs are not critically evaluated and improved. The forces that monitor the effectiveness of domestic government programs are lacking. The few studies of such programs, mainly by writers and journalists from industrialized countries, indicate the results of this situation (Linden, 1976, Paddock, 1973, Sterling, 1976). Agricultural development projects turn out to be ecologically unsound, training projects produce graduates who cannot find jobs, equipment lies idle for lack of maintenance, and so on.

Fortunately, institutional and political forces are not the only forces in the system. Many of the individuals involved in technical assistance, the administrators, the experts, and the recipient officials, take seriously the idea that the programs are intended for the welfare of the people and resist, to a greater or lesser extent, the institutional and political forces.

Projects that have been successful in transferring technology have often achieved their accomplishments through the efforts of one person who combines political and management skills with technical competence. When a project is small enough to be run by one person, and a person who combines these skills is available, the chances of success are good. When such exceptional individuals are not available or when a project is too large, the required political, managerial and technical skills must be institutionalized. Since most technical assistance programs pay little attention to management problems, this is rarely achieved.

The problem of acquiring the variety of skills required can probably be solved more easily in a permanent program than in a short term project. A permanent institution is more likely to attract and can afford to train competent staff and can accumulate the experience of a variety of projects over a long period of time as individual experts come and go. The establishment of an institution with specific function of transferring remote sensing technology as a long term program between a group of

industrialized countries and a group of third world countries might provide a means for overcoming some of the problems discussed above.

2. TECHNICAL ASSISTANCE INSTITUTIONS

2.1. The United Nations

The United Nations consists of 148 member governments whose representatives meet annually in the General Assembly and its committees and sub-committees. The U.N. Secretariat carries out the instructions of the member governments. Since all authority derives from the governments, and since all governments are regarded as equal, all U.N. technical assistance must be available to all governments without restrictive selection criteria, and no action can be taken which might offend any member government. As a result, no critical evaluation of projects can be carried out by the Secretariat, and the committees and sub-committees have neither the time nor the competence to do the job. To the extent that programs are evaluated, this consists of a review of the number of projects and the number of people and countries involved. There is, therefore, a pressure to spread resources thinly to increase these numbers.

The main source of funding for technical assistance in the U.N. is the United Nations Development Program (UNDP) which distributes about \$400 Million annually among the third world member governments. To put this figure into perspective, it is somewhat less than the aid given by Canada and about one tenth of the foreign aid given by the United States. The UNDP allocates a share of this money to each government, and the government tells the UNDP how it wishes the money to be spent. The function of the UNDP is to assist the government in acquiring the desired experts and materials, not to criticize the projects or study the results. Since the priorities are established by the recipient governments, the UNDP does not promote remote sensing or any other particular technology, but a number of governments have funded remote sensing projects through the UNDP.

The U.N. program that does promote the transfer of remote sensing technology is the Space Applications Programme which operates with a staff of four professionals and a budget of about \$100,000 per year. The main effort is the organization of about four seminars each year, two or three of which deal with remote sensing. Since this allows about \$20,000 to be spent on each seminar, and since the total expenses for each are about \$50,000, the program is dependent on outside financial support. This is obtained by finding a host country to provide facilities and administrative support, by requesting industrialized countries to contribute lecturers, and by obtaining contributions from other technical assistance agencies. This additional support increases the number of participants and countries that can be involved in the program, but reduces the control that the U.N. has over organization, subject matter, and ultimately, effectiveness. There is generally little money available for course preparation, evaluation or follow-up contact with students.

The Space Applications Program has been organizing training seminars since 1971, and while its financial and technical resources are rather limited, it has more organizational experience than any other technical assistance agency. The U.N. Expert on Space Applications is exploring ways to combine that experience with the technical and financial resources available in the industrialized countries to overcome the limitations imposed on the program. One of the seminars tentatively planned for 1978 will be funded largely by the Swedish government and will be held in Africa using the experience of some of the established resource survey projects there. This sort of cooperation may allow more time, effort and money to be put into the preparation of course materials.

2.2 The Food and Agriculture Organization (FAO)

The FAO is the U.N. agency responsible for projects in the fields of agriculture, forestry and renewable resources in general. While many of the resource survey projects include a remote sensing component, most are not part of any coordinated effort to transfer the technology.

Like most technical assistance agencies, the FAO has a policy emphasizing field work as opposed to work at headquarters in Rome. Since field projects are usually carried out by experts recruited for the duration of the project, there is little opportunity for the accumulation of experience or expertise at headquarters where the planning, coordination and evaluation of the program must be done.

In recognition of the potential contribution of remote sensing to the development of renewable resources, the FAO has established a Remote Sensing Unit to provide facilities, expertise and services both to FAO projects and to other programs in member countries. The resources of the unit are applied to third world problems in three ways: by assisting scientists from industrialized countries working in the third world; by assisting third world scientists in gaining an appreciation of remote sensing; and by organizing training courses for third world scientists. A number of workshops are held in developing countries each year, and one or two more specialized courses are held at headquarters where more resources are available for preparation, instruction and evaluation. Since the function of the unit is to provide services upon request, most activities are short term with little follow-up, and there is limited opportunity to develop expertise in particular applications or to study in detail the process of transfer of technology.

2.3 The World Bank (IBRD)

The World Bank, another member of the U.N. family, funds large scale, operational development projects selected on the basis of expected economic return on investment. The Bank does not fund research and development projects or training courses although training may form part of a larger project.

The World Bank has a two person remote sensing office to introduce the technology into resource survey projects where economically justifiable. This generally involves supplying computer classified imagery which is then checked in the field. The Bank recognizes that few third world countries can acquire the capacity for this sort of processing but feels that this approach will more effectively lead to economic development.

2.4 United States Agency for International Development (USAID)

USAID has established an Office of Science and Technology specifically to promote the transfer of technology, and this office has the only substantial national program to promote the application of remote sensing in the third world. The first efforts in this program were the organization of a number of seminars, both in the U.S. and in the third world, to create an awareness of the existence of the technology. While USAID continues to support training seminars from time to time, the emphasis subsequently changed to a grants program, the projects of which are still underway. To encourage the development of local capability, USAID solicited proposals for small scale research and development projects from third world scientists and provided the necessary expert assistance and materials to carry out the projects. These projects will be completed and evaluated in the next year or two.

The funds available for the remote sensing program are expanding very rapidly, from about \$500,000 in 1976, to \$1,000,000 in 1977, to about \$5,000,000 in 1978. With this funding, USAID is now planning support for regional remote sensing centers. Such a facility for East Africa is currently being established in Nairobi, and consideration is being given, in cooperation with Canada, France, and the Economic Commission for Africa, to the establishment of a West African center in Upper Volta.

2.5 Canadian Technical Assistance

There are two technical assistance agencies in Canada, both of which have developed an interest in remote sensing. The International Development Research Center (IDRC), which was established to fund and study small scale research and development projects, has funded four projects in remote sensing. These were selected by identifying third world scientists who had initiated remote sensing

projects, had demonstrated competence as both managers and scientists, and who needed support to develop their projects further. While additional projects will probably not be funded until the results of these projects have been evaluated, IDRC is interested in studying the possibility of regional centers. The Canadian International Development Agency (CIDA) has acquired an interest in remote sensing more recently and has just started funding a substantial project to develop remote sensing capabilities in Peru. CIDA is currently considering funding for the West African center, and, as in the case of USAID, may be substantially increasing its remote sensing assistance in the next few years.

3. CONCLUSION

Review of technical assistance programs have shown that many projects have had destructive consequences and very few have achieved the results that were intended. The political forces involved discourage the critical review that is necessary if this situation is to be improved. At present none of the institutions involved in technical assistance have a vested interest in the long term contribution that transfer of technology can make to economic development.

In remote sensing, projects have been very small until now, and individuals interested in effective projects have been able to resist some of the political pressures. With the present rapid growth in funding of remote sensing projects, the political pressures will increase and the influence of individuals will decrease. While it is not possible to eliminate the political forces from the system, it may be possible to establish research and development institutions, on a cooperative basis between industrialized and third world countries, which can control and focus the process of transfer of technology. The present interest in regional remote sensing centers would appear to be healthy providing that political factors are taken into account in establishing the centers and that cultural and economic factors are considered in the implementation of projects. The centers should be regarded as long term cooperative programs rather than as short term assistance projects.

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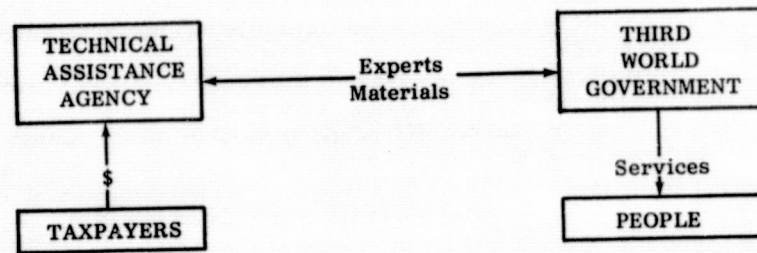


FIGURE 1. TECHNICAL ASSISTANCE

THE TRANSFER OF REMOTE SENSING TECHNOLOGY¹
IN THE DEVELOPING NATIONS - AN OBSERVATION¹

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ABSTRACT

Although some nations are still to grasp the full impact of aerial survey in their development efforts, they are nevertheless yearning to take advantage of recent developments and progress in space science and technology. In this regard, the co-operation and assistance of the industrialized nations, and the U.N. and its agencies through training programs, workshops, and seminars, and the on-going globally scattered demonstration projects are highly commendable. These efforts have resulted in the development and growth of remote sensing centres in a number of nations. Unco-ordinated efforts rather than lack of interest, scepticism, and suspicion have however slowed its progress in others.

Emphasis should shift from centralized training to scheduled regional training programs, resulting in larger local participation and on-the-spot application of the technology to solve local problems. Developing countries should be encouraged to develop technological capability that will result in local analysis of the remote sensing data of their regions instead of contracting it out to firms in industrialized nations.

Communication gaps exist between the U.N., its agencies and the industrialized nations on one hand, and those who can effectively transfer remote sensing technology in the developing nations on the other. These gaps have been identified and remedies have been suggested. The technological gap resulting from the inability of the developing countries to keep pace with the growth and development of different types of remote sensing systems and the subsequent implications are examined.

Although remote sensing technology offers a very great potential, attempts, however, at marketing its unproven capability and/or at down-playing the role and importance of ground-truthing may encourage over dependence on this technology. The contributions of firms and agencies from the industrialized nations in this respect are analyzed. Neighboring countries should always be encouraged to evolve their own remote sensing plans; efforts channelled in this direction will accelerate the transfer of this technology in these regions.

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INTRODUCTION

In the late 1950s and early 1960s, when the European countries were losing their grips on their former colonies through the attainment of political sovereignty, research and development efforts in both the United States and the USSR were directed at conquering the outer space. The technology and equipment that resulted from these efforts were subsequently tested on the Vostok, Voshkod, Mercury, Gemini and Apollo space vehicles (IAF, 1974), and are now finding wide applications in the global explorations of space. Such explorations include, among others, the use of electro-magnetic sensors placed on board various aerial and space platforms to evaluate the extent, classification, quality, and temporal and spatial changes of earth resources. This is the heart of what is generally known today, as remote sensing of the environment.

Remote sensing is gradually becoming the dominant method for conducting earth resources surveys and analyses in the industrialized as well as in a few developing countries today. In particular, since 1972, experimental satellites such as LANDSAT-1 and -2 which are still in orbit, and experimental space stations such as SKYLAB have collected data over most parts of the globe in the course of their respective missions. And typical investigations characteristic of remote sensing of the environment include those on (General Electric, 1974) agriculture; forestry and range management; water resources; geology; marine and oceanography; energy sources; environment; and land use; mapping and charting.

DEVELOPING NATIONS AND DEVELOPMENT DATA

A major task that faces most of the developing nations today is how to achieve a better standard of living and attain self-supporting growth within a relatively short period of time. The typical investigations listed above can assist in the solution of these problems. Specifically, these nations should evolve plans that will enable them to optimize the utilization of their natural resources and physical surroundings. These include the optimal exploitation of the productive resources of their land in particular, and the planet as a whole.

Inadequacy of Data

National plans of this nature are regular features of global development efforts. In formulating them, background information is often extracted from existing or synthesized data whose reliability is dependent on the accuracy and completeness of the available exploratory or historical information. Unfortunately, many of the programs launched through such plans are frequently beset by inaccurate projections (Abiodun, 1973; Mendoca, 1975) and a chain of uncertainties even before the schemes are initiated. In Nigeria for example, (Asiodu, 1975), "in the case of the iron and steel complex it was soon clear that the basic information on quality, characteristics and quantity of the available primary raw materials was not available and these had to be developed before any work could start on designing the complex, let alone constructing it. What was to be started during the 1970-74 Plan Period may now not start until 1980. Furthermore, in the case of the cement industry, inadequate geological investigation led to the wrong choice of technology".

These few examples highlight the increasingly difficult tasks these nations face in marshalling the needed man-power to undertake resources surveys and data collection exercises using the well known conventional methods. In most of them, the full impact of aerial photography in their development efforts is still to be appreciated, man-power and cost being the two most deciding factors. Where such techniques have been used, the organizational set-up, execution and control are in the hands of foreign consultants, while the financial backing for its implementation has evolved, in general, through bilateral agreements.

With or without data, development schemes are conceived, planned and executed. The unknown element, however, is the future cost of such programs. In order to avoid unnecessary waste of scarce but highly skilled human and other resources these nations should find new ways for exploring and harnessing their natural and environmental resources; they should first embark, in earnest, on the assembly, analysis and dissemination of vital information on these resources and systems: remote sensing has been technically and financially demonstrated to be capable in assisting in this effort.

Remote Sensing Feasibility

The successful applications of remote sensing technology in many parts of the world are numerous and most of these have been documented. In Mali, for example, remotely sensed data were used (MacLeod, 1973) to monitor the impact of the Sahelian drought on the life of Maleans. Ghana's Council for Scientific and Industrial Research in collaboration with the United States Agency for International Development assessed (Dodoo, 1975) deforestation and over-grazing in northeastern Ghana Savannah through the use of the imagery and spectral data of LANDSAT-1 and -2. An analysis of the synoptic patterns of distribution of suspended load in Lake Kainji, Nigeria (Abiodun, 1976) at the beginning of the annual floods was performed using LANDSAT-1 data.

Nations such as Bolivia (Brockman, 1973), South Africa (Viljoen, 1973), and Egypt (Shazly, et al. 1973) have also found LANDSAT data to be invaluable in locating new targets, in aiding the exploration of fracture-controlled mineral deposits, in relating earthquakes with their causes and in noting potential hazards in mining and construction. LANDSAT-1 results were utilized to locate possible areas of copper deposits in Pakistan. The rapid developments in many parts of the world such as in Brazil (Mendoca, 1975) and Canada (Fleming, 1975) would be very difficult if not impossible to incorporate into the existing maps without the aid of an orbiting space vehicle. Its repetitive coverage permits accurate delineation of numerous features such as the land-water interface. Oil exploration is equally in the remote sensing picture. Although majority of the oil companies are very reluctant (Mathews, 1975) to discuss the successes they have achieved by using satellite data, known oil fields in well mapped regions have been found to display special tones on LANDSAT images. Finally the FAO is currently executing a number of pilot projects (FAO, 1973) using space imagery, in activities related to survey and development of land, water and forestry resources in a number of the developing countries. Sample results of remote sensing applications in Sierra-Leone and Nigeria, by the author, are also shown in Figures 1 and 2.

A deliberate effort has been made above to cite examples of remote sensing applications in the developing countries. Firstly, it should be noted that remote sensing is being used in the non-industrialized world to break new grounds and to locate new targets (Figure 2); the industrialized nations on the other hand have reached such mile-stones decades ago through the use of conventional methods including aerial surveying. In short, the dependence of the developing nations on remotely sensed data for natural resources surveys is greater than that of the industrialized nations for the same purpose. The response of the developing nations to the UN questionnaire (A/AC.105/143, 1975) on priority needs in space exploration clearly attests to this.

Furthermore, most of the individuals who carried out the projects/research work cited above executed their missions, not in the local areas affected, but in foreign laboratories and offices. The on-going FAO projects use foreign experts as project executors, and there are many instances where non-local people are employed to obtain ground truth data. If this trend continues, will remote sensing not remain remote for citizens of the developing segment of the world? Or are these attempts intended to convince the developing countries that remote sensing can assist them in their development efforts? If so, how have the industrialized countries and the agencies of the United Nations fared in this technology transfer process? And what is the attitude of the recipient nations?

Framed in another manner, the concern here is not one of identifying the type and nature of assistance sought by the developing countries in the area of space applications. These have been well documented (A/AC.105/143, 1975). The aim, however, is to focus attention on how the technical assistance programs have been or are being executed, and to single out the main obstacles, if any, that might hinder an effective and responsible transfer and application of this technology.

REMOTE SENSING TECHNOLOGY TRANSFER TO DATE

The pre-occupation of the developing countries with political stability and economic survival, coupled with shortage of highly skilled man-power, has resulted in their being great consumers, not only of products, but also of undiluted imported technology. Except in a very few unique cases, the role of these nations in the field of space science and technology has been limited to the granting of territorial rights to technology producing nations to install and operate observatory posts as was the case in Kenya, during the Gemini and Apollo missions, and to the reception of Automatic Picture Transmission (APT) images from United States meteorological satellites for weather forecasting purposes.

External Contributions

It thus became apparent that if the developing nations were to benefit from this technology, a measure of assistance must be provided through bilateral arrangements and through the agencies of the United Nations. The variety of assistance offered to-date are too numerous to document here. It is sufficient to state, however, that they have ranged from training programs, fellowships and pilot projects sponsored by the UN and its agencies, and the industrialized nations, to bilateral arrangements for the same purpose. Ghana and Kenya on one hand and Peru on the other have benefited from the latter arrangements from the United States and Canada respectively. In addition, specific contributions aimed at effecting the transfer of this technology have also come from regional economic groups (ECA, 1976) and sovereign governments (W. Germany, 1975).

Experimental - Operational Phase

Most of the efforts cited above, however, centre on satellite technology. LANDSAT-1 and -2 are experimental satellites. This will equally be true, although at an advanced level, for LANDSAT-C which is to be launched this year. The concern of the developing countries is that there is no firm assurance (Anderson, 1974, STSC-PUOS, 1976) that the program will be continued beyond the technology demonstration phase. Should the current experimental phase fail to graduate into a full operational program, the developing countries will be hard pressed to absorb the cost of equipment and man-power training that may not yield immediate returns not to even mention the disappointment that would be felt in a number of quarters. It can be argued that such man-power and equipment would easily find application in similar programs of other industrial nations including earth survey satellites of France, the USSR or the Federal Republic of Germany.

It is reasonable, however, to expect that these programs will also go through the normal experimental phase before they become operational. There is also no guarantee that in an attempt to track earth resources satellites other than those in the LANDSAT series, expensive equipment modification will not have to be undertaken in the tracking mechanisms of a number of ground receiving stations. In particular, remote sensing technology is breaking new ground every day. Future satellites will be more sophisticated than the existing ones and will be designed to operate within the x-band or higher radio frequencies instead of the s-band frequency (IAF, 1974) used for the present generation of satellites.

National-Regional Stations

In spite of the lack of assurance highlighted above, strong efforts are being made to establish a number of regional ground-receiving and processing stations in several parts of the world. In the same spirit programs aimed at establishing regional training centres have in a number of instances progressed beyond the feasibility stage. A quick look at the existing stations in the United States, Canada, Brazil, Italy and the one under construction in Iran are similar in one respect. They are all national stations, although some of them are serving regional interests. Outside Europe and North America, two stations are being managed by countries that are financially and technologically (man-power-wise) as solvent, if not more so, as their neighbours. Can we say the same for those areas of the developing world where "national" stations are now being proposed as "regional" stations?

The general view prevailing in the UN Committee on the Peaceful Uses of Outer Space (A/AC.105/154, 1976) is that future operational remote sensing activity can be more effectively accomplished through regional cooperation. In this context, one is tempted to believe that such regional stations would be established right from the out-set through proper regional consultation. In essence the ramifications of establishing a station, including staff development, infra-structural problems and country-by-country financial outlay would be resolved by all the nations concerned before a blue-print of the station is presented to the public. The prevailing trend, however, is contrary to this.

In fact, the emerging pattern is to suggest the conversion of a proposed national station into a regional one (ECA, 1976). This, of course, is inevitable if the potential owners of such stations ever expect to recover their huge investments. If the industrialized countries are truly committed to transferring remote sensing technology in the developing countries, they should ascertain the level of support such a station would enjoy within the region as well as conscientiously help establish the actual viability of the station before they in turn commit themselves to establishing it. The on-going attempts, to promote regional stations without actually involving the countries that geographically make up the region to be served is very counter-productive and does not contribute positively to the technology transfer effort. In this connexion, one should also observe that the agreements already reached with industrialized nations for the establishment of the aforementioned stations are making it difficult, if not entirely impossible, for other countries within the regions to negotiate for the establishment of smaller ground receiving stations of their own.

Furthermore, the impressive catalogue of results obtained to date through satellite survey of earth resources of the developing nations came about principally because the satellites in question had on-board recording systems. Similar efforts, however, cannot be undertaken when a number of the new generation of satellites, which will not have any on-board recording system, are launched. In particular, the developing nations cannot and will not derive any direct benefit from the missions of such advanced satellites (IAF, 1974) as the Heat Capacity Mapping Mission (HCMM) satellite scheduled for launch this year. In the same vein, the Ocean Dynamics Measuring Satellite - SEASAT-A (the Coherent Imaging Radar portion of it) and the Earth Observation Satellite (EOS) just to name a few, are satellites with no on-board recording systems, which the developing nations will only hear about, but will not have an opportunity to know about. Bearing in mind the details of the missions of future satellites, most developing countries are at a major disadvantage, more especially since they are geographically placed in regions of the world where there is no concrete evidence to show that proposed regional plans to build tracking stations will materialize soon enough to receive information from the planning space platforms.

External Control of Activities

If remote sensing technology is to be effectively transferred into an area, it is essential that the local citizens of that area be involved in the exercise. This appears to be the logical interpretation one would give to the view of the Committee on the Peaceful Uses of Outer Space on the subject: "It should be emphasized that accurate interpretation can only be done by interpreters familiar with the area concerned" (A/AC.105/143, 1975). Most of the published and on-going works on remote sensing application, in respect of the developing countries are being executed by individuals who are far removed from the scenes of operation. These exercises would be more meaningful to the local citizens if they are executed on site.

The unrestricted access to LANDSAT data on the other hand, has resulted in the establishment, in the industrialized nations, of a new breed of organizations. Despite their shallow or non-existing knowledge of the local area, they have nevertheless embarked upon the production of "beautiful" satellite pictures for decision makers in many developing countries. There is now the problem of coping with the flood of unsolicited remote sensing proposals (FEDWATER, 1976) backed up by local satellite images from different companies and individuals, albeit to the consternation of the local authorities. In general, many of these proposals portray the use of remote sensing techniques as the sole answer to earth resources survey in the local area concerned, with little or no consideration being given to the importance of ground-truth.

Many such jobs are already being contracted out on the premise that no indigenous company could handle the "sophisticated" assignments. In other situations, where aerial survey data are still to be exhaustively and extensively employed in the development process, major efforts are under way to utilize airborne radar systems offered by foreign firms, (without any local citizen trained in the discipline) to monitor the resources of the local area. Although such a bold effort may be genuinely aimed at hastening the national development process, it might sooner or later result in debates over the security and the sovereignty of the nation/s concerned. At that stage, the situation may be explosive.

In addition, cost of data processing equipment is a serious constraint in the technology transfer process. It is obvious that the computer processing techniques offer the greatest details of accuracy in interpretation. Even where the existence of technical capability would justify an investment in such a process, the current costs have made the application of the computer techniques impossible.

Program Centralization and Effective Leadership

As a means of facilitating and accelerating the technology transfer process, the Committee on the Peaceful Uses of Outer Space (CPUOS) has stated that (A/AC.105/143, 1975):

"Appropriate people in the country must become aware of and interested in the potential benefits of the new technology, and a small multidisciplinary group to study the economic benefits and the technical feasibility of introducing the technology into the country must be organized".

COSPAR went a step further (A/AC.105/165, 1976) and

"Recommends that young people be selected for extensive periods of training in remote sensing techniques at centres of expertise".

These views constitute the focal point of the success or failure of remote sensing technology transfer in many developing countries today. And where the transfer effort has failed, the greatest obstacle has been none other than a core of the citizens of that same country. Hence the logical question to ask at this stage is: What have been the contributions of the developing countries

to the success or otherwise of remote sensing technology transfer within their geographical boundaries?

The current approach in Ghana, for example, (Abiodun, 1975), is towards the establishment of a multi-disciplinary remote sensing centre which would function under the umbrella of the country's Council for Scientific and Industrial Research (CSIR). It was with this in mind that CSIR, in collaboration with the United States Information Service in Ghana, convened the first remote sensing conference in that country in April, 1975. Ghanaians within the government and the universities were sufficiently satisfied with the manner in which the council handled the conference that they now thereafter looked upon CSIR for leadership and guidance in remote sensing technology. Similar examples prevail in other places including Egypt where remote sensing activities are being guided by the National Academy of Scientific Research (ECA, 1976). The Egyptian program, with an investment of up to \$1 million in equipment, concentrates on the application of remote sensing technology in development projects. Egypt also successfully hosted the UN sponsored Workshop on Remote Sensing in November 1974.

Not all the developing countries, however, have been so lucky: a handful of the local citizens, and NOT the countries themselves, are responsible. CPUOS and COSPAR cited "appropriate" and "young" people respectively as being the centre of dissemination of remote sensing knowledge. Are these concepts being universally followed? What have been the contributions to the progress or stagnation of this new technology by those in positions of scientific leadership in the developing nations?

A survey of the academic and professional background, position and age of some individuals who have participated in international remote sensing training programs, ranging from the COSPAR sponsored workshop in Brazil in June 1974 to the FAO sponsored training program in Rome in October 1976 showed that a number of these individuals were not the most suitable candidates for the workshop. At an early stage of the training, such candidates often discover that they are no longer interested in the program or would eventually not be able to make use of the training. Often, they simply fail to appear for the remainder of the course. A participant from a prominent developing country did just that after three days at the 19-day 1974 COSPAR workshop in Brazil, (Workshop Records). On returning home, such candidates are not in a position to contribute to the transfer of the new technology. Simply stated, their participation is a waste of the public's resources and a gross misrepresentation of the countries affected. Those countries would have benefited more if the "appropriate" people had been selected at the outset.

In general, decision makers in the developing countries are very receptive to innovative ideas if such ideas ever make it to their desks. A number of them would be keenly interested in remote sensing technology, for development purposes, if only they could be properly briefed. Unfortunately, the red tapes are too restrictive. It is erroneous to assume that items of information dispatched from the UN, its agencies or from the industrialized nations do not reach the developing countries concerned. The problem is that where there is no centralized authority, the in-coming information may fall into a wrong or disinterested hand. It is not uncommon, thereafter, for such information never to see the light of day again. Hence, the participation of such country/ies becomes very chancy.

Furthermore, there is the problem of competing and/or conflicting personalities within a given institution that may be interested in developing remote sensing technology, or of competing institutions or agencies for the control of remote sensing activities within a given country. In these circumstances, the "appropriate" people will never be informed about relevant remote sensing news and programs, irrespective of the source of the information.

FUTURE EFFORTS IN THE TECHNOLOGY TRANSFER PROCESS

To date, the efforts devoted to the transfer of remote sensing technology in the developing countries have met with both success and failure. Where problems exist, the developing and the industrialized nations should identify them and strive to minimize if not totally eliminate these obstacles.

Role of the UN, Its Agencies and the Industrialized Nations

Those who seek to help transfer a respectable remote sensing knowledge or technology should ascertain that their efforts and/or contributions ensure the preparedness of the users of the technology. In this context, any program planned should include the understanding and the appreciation of remote sensing through participatory efforts in the development of the appropriate space platforms, data reception mechanisms, and in meaningful applications of remotely sensed data.

For a variety of reasons, a few of which have been cited above, efforts to establish ground receiving and processing stations in a number of the developing regions of the world have stagnated. This is not helpful to many of the developing countries so affected, since valuable data of their natural resources are being lost forever. Hence there is an urgent need for countries producing satellite remote sensing data to reach an understanding with those developing countries that can afford to, and have indicated their desire to establish ground receiving stations of their own.

It is equally necessary to determine the feasibility of using some of the existing communication facilities for earth resources data reception. Specifically, it should be technologically possible for the earth resources satellites to communicate with the geo-stationary communication satellites. The latter can retransmit information to the existing ground communication stations where remote sensing data can be received and processed. If this approach becomes feasible, it will go along way towards the promotion of the transfer of the new technology.

As a result of lack of adequate interpretation facilities in a number of the developing countries, many of the remote sensing jobs in these areas are often contracted out. In the long run, this approach cannot be viewed to be in the best interest of the developing nations. If the latter are ever to look after their own economic interests, they should be encouraged to extract maximum information THEMSELVES from any existing or future satellite data acquired over their territories.

Extraction of maximum information from satellite imagery requires the utilization of digital analysis systems. The costs involved in the acquisition of this type of equipment (e.g. LARSYS, IMAGE-100) and the necessary software are astronomical; the 1976 prices of hardware alone ranged from \$300,000 to over \$1 million (Strome, 1976). This certainly, is beyond the financial means of many developing countries. It would be desirable to produce systems with a capital cost on the order of \$50,000 if digital image analysis is to be brought within the reach of the developing nations (Strome, 1976). The industrialized nations and their digital computer manufacturing companies should consider it a challenge as well as a worthwhile goal to produce such an image analysis facility.

On the training aspect of remote sensing, there is a need to establish permanent training centres in the developing regions. By so doing, many local people can be trained, local problems in which remote sensing can effectively be applied identified, and pilot projects attempted; views can also be readily exchanged among experts and a host of local trainees. Opportunities of this nature will enable the experts to calm the fears of the local people as well as to remove any misconception about the overall goal of remote sensing. It is equally possible that the host country might be convinced at an appropriate time to make a major investment in relevant equipment, thus paving the way for an effective transfer of the new technology.

There will still be the need, however, for young people to undergo periods of extensive as well as short training at centres of expertise. On such occasions, it will be very necessary that "appropriate" people be selected for such training programs. In this respect, the manner in which the Centre National d'Etudes Spatiales (CNES) of France selected candidates from the developing countries for participation in the 1973 UN sponsored Summer School on Remote Sensing of Earth Resources is worthy of emulation, and is hereby recommended for adoption at future training/workshop sessions.

Role of the Developing Nations

As a matter of urgency, the developing countries should critically review their practice of importing new technology and foreign personnel to execute their development projects without actually encouraging their own citizens to participate, along-side the expatriates in the exercise. In a given situation where the assignment involves the gathering of remote sensing data using the air-borne platforms of the foreign firm, it would be desirable to give basic training in the requisite technology in advance, at home or abroad, to a core of local qualified people. It would be equally desirable to request the incoming organization to make room for the active participation of the local group at every stage of the project. This would ensure that the data so acquired will not gather dust once the foreign party leaves, but will be gainfully employed in the national development effort. The home government will also have an opportunity to exercise the necessary control, especially where security matters are concerned.

The inability of the outside world, on the other hand, to identify the appropriate authority in a particular country may be responsible for much of the haphazard nature of remote sensing technology transfer to date. Thus it is necessary that developing countries centralize their remote sensing activities; identify those within the country who, by their training and professional practice, can be employed in the development of the country's short and long-range remote sensing goals; and establish an effective and appropriate authority, as is the case in Ghana or Egypt, to champion the cause of remote sensing nationally. That authority must be responsible for receiving and disseminating remote sensing information to people who are "aware of and interested in the potential benefits of the new technology".

Finally, it should be clearly understood by those aspiring to establish national or regional ground receiving and processing stations that such programs require a combination of adequate and functional infra-structures including electric power supply, communication systems, highly skilled technology-oriented man-power, and financial resources. A developing country that cannot provide these ingredients, which are essential for a successful operation of ground stations, is not in a position to offer any technological leadership within its regions. The progress or stagnation of neighbouring states may depend on the success or failure of that station. And the reliance of the latter on massive imported man-power is not in tune with the reality of this politically conscious world.

CONCLUSION

Much has been done, to the credit of the United Nations, its specialized agencies, and the industrialized countries, to promote the application of remote sensing technology in enhancing economic development in the developing countries. Where the efforts have failed to yield any meaningful result, it is the joint responsibility of all concerned, within and without, to identify the obstacles and strive to minimize or eliminate them completely. It is equally pertinent to ask those who seek to transfer remote sensing technology or knowledge in the developing countries, to have a clearer understanding of the actual motives behind their transfer efforts.

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Existing Map



LANDSAT-1, Jan. 8, 1974

■ Mangrove Swamps ■ Forest Regrowth & Farmland ■ Lophira Tree Savanna & Grasslands
 ▨ Thick Forest

Scale 1:650,000

FIG.1: VEGETATION MAP OF WESTERN SIERRA-LEONE

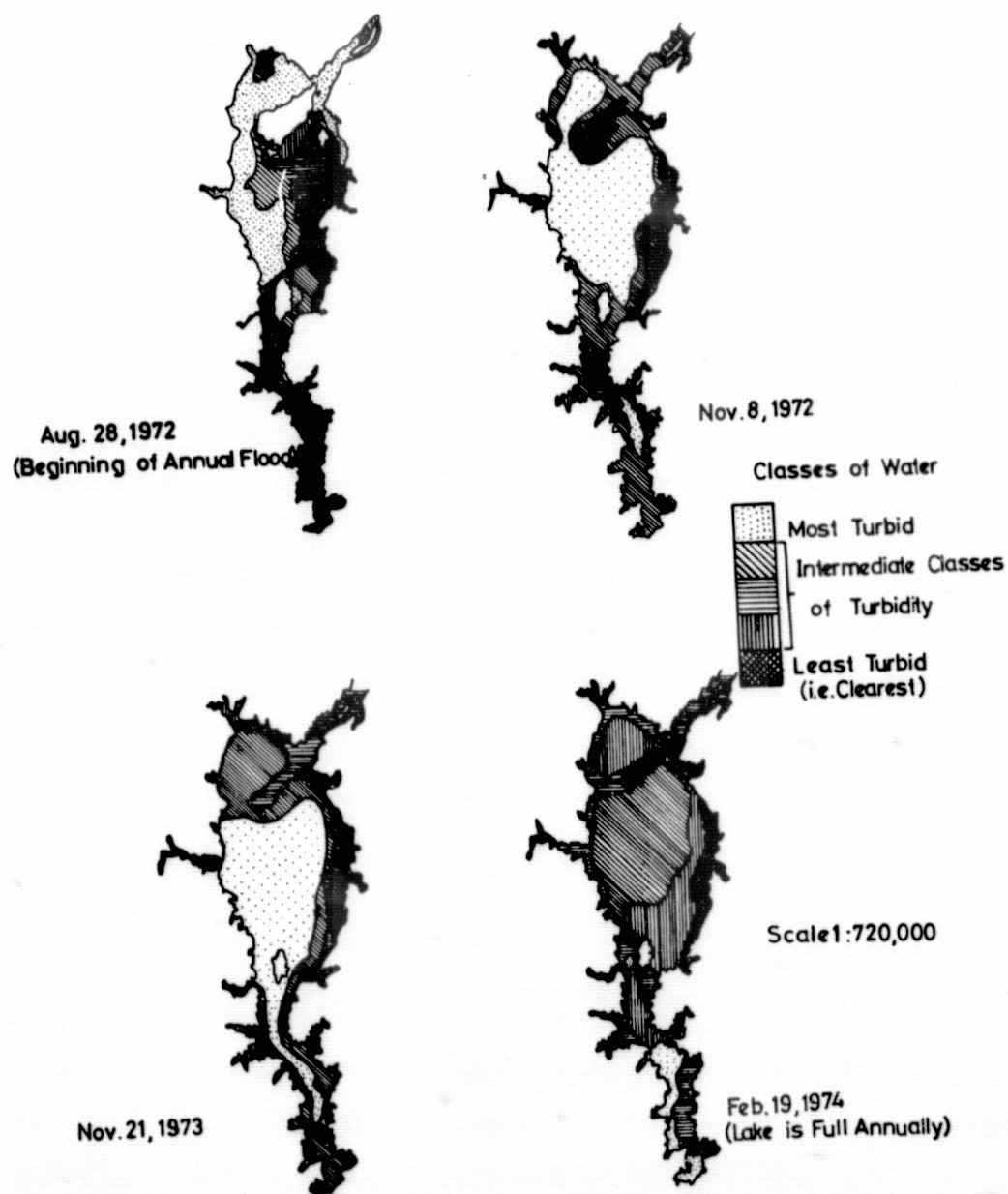


Fig. 2: Movement of Water Columns in Lake Kainji, Nigeria (LANDSAT-1)

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REMOTE SENSING OF AIR POLLUTANTS

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ABSTRACT

This paper deals with monitoring of those pollutants within the troposphere which the U.S. Environmental Protection Agency is required to control by the Clean Air Act of 1970. We limit ourselves to discussion of selected specific techniques and attempt to show how the use of these techniques fits into the overall national strategy for air pollution abatement.

INTRODUCTION

Any instrument builder must first define the needs of the user in setting out to construct a new device, and the builder of air pollution instrumentation is well-advised to do likewise. The instrument builder needs to ask questions about the data required of his instrument: Who is the user? What kind of data does he desire? What will he do with this data, and what legal role will the data play?

To understand the needs of users of air quality monitoring data, a brief overview of national efforts to achieve clean air is useful. Figure 1 shows the process outlined by the Clean Air Act of 1970. The first step required by the Clean Air Act is the promulgation of National Ambient Air Quality Standards (NAAQS). The NAAQS are primarily based on research into the health effects of various pollutants and are the goals toward which the entire air pollution abatement effort is aimed. The Clean Air Act specifies "primary" and "secondary" standards; the primary standards are health-related, while the secondary standards are welfare-related.(1) The primary standards represent immediate urgent goals, while the more stringent secondary standards can be regarded as long-range goals.

An ambient air quality standard is intended to limit the total exposure to a specific pollutant or class of pollutants to which a member of the general public may be subject. Thus it is usually written in terms of a concentration averaged over a given period of time. The average concentration must be measured at a location accessible to a member of the general public.(2) One implication of this aspect of the NAAQS for remote sensing is that the concentration must be measured continuously at a fixed location; another is that the concentrations must be measured in air which a member of the public could breathe and not at an elevation considerably above head height. Another implication for remote sensing which has not received much attention, but which perhaps should be considered, is that the concentration probably ought to be averaged over an area no larger than the area in which a member of the public might confine himself during the minimum averaging time of 1 hour. To insure comparability of measurements, a specific reference measurement technique was identified for each pollutant covered by a standard. New methods must demonstrate equivalency to the reference methods by satisfying a set of criteria.(3)

Ambient air quality standards have been established for sulfur dioxide, total suspended particulates, carbon monoxide, photochemical oxidants, and nitrogen dioxide. An advisory standard for non-methane hydrocarbons was also established as a guide in developing control strategies for photochemical oxidants.(2) An ambient air quality standard for particulate lead has been proposed, and a standard for particulate sulfates is under consideration.

The next step in the abatement process after setting the NAAQS is to implement the standard by establishing a strategy for emission regulations. The Clean Air Act requires that each state develop a State Implementation Plan (SIP) outlining its strategy for meeting the NAAQS; these plans are to be submitted to the U.S. Environmental Protection Agency (EPA) for approval within 9 months of the promulgation of a NAAQS for the subject pollutant. The Clean Air Act further requires that, when the state fails to submit a SIP, the EPA is required to develop one. The SIP is essentially a set of emission regulations, usually based upon the modeled dispersion of pollutants from specific sources. To give a technical basis for SIP emission regulations, the less complex models relate the emissions from large point sources to ambient concentrations. The models themselves consist of basic dispersion equations which perform their calculations from a mix of measured, estimated, and assumed parameters. For example, dispersion from point sources is usually modeled with some type of Gaussian dispersion formulation, using estimates for plume centerline height-of-rise, crosswind and vertical dispersion coefficients, atmospheric stability, mixing depth, and mean wind velocity. Plume height-of-rise is estimated with empirical formulas from heat flux, momentum flux, stack height, effluent and ambient temperature, stability, and vertical wind profile.

The final technical step in the abatement process after implementation of the control strategy is to monitor ambient air in the affected geographic area to ensure compliance. This again involves measurement of concentration averages at fixed locations to compare the data with the NAAQS. One of the major technical problems encountered in compliance monitoring is the design of the monitoring network to ensure that violations of the NAAQS in the air quality control region are observed. Another form of compliance monitoring is in-stack emission monitoring to ensure that the SIP emission regulations are met.

Figure 1 reveals some specific air quality monitoring needs related to each step of the abatement process. First, the setting of ambient air quality standards requires the establishment of dose-effect relationships. This usually involves epidemiologic studies in conjunction with air quality monitoring studies, as well as laboratory dose-effect studies. For example, the primary ambient air quality standard for sulfur dioxide was established on the basis of all data available in 1970 about the health effects of the pollutant.(4) Subsequent health-related monitoring and epidemiological studies such as the Community Health and Environmental Surveillance System and Community Health Air Monitoring Program have been carried out as reviews of the original health-effects criteria.

The SIP is typically a set of emission regulations based on models which relate emissions to ambient concentrations. An investment in air quality monitoring, particularly in remote sensing techniques, can reduce model uncertainty by replacing estimated or assumed critical parameters with actual measurements. For example, the accuracy of a Gaussian point source dispersion model can be improved by supplying it with actual measurements of plume centerline heights, centerline concentrations, vertical and horizontal dispersion coefficients, and transport winds. Another type of monitoring related to SIP development is concerned with quantifying the effects of long-distance transport of pollutants. Much recent work has been concerned with the considerable impact of the transport of photochemical oxidant and/or its precursors over distances of hundreds of miles.(5) The desired end product of this type of study is a model establishing a quantitative relationship between the transport phenomena and oxidant concentrations at a receptor location. A model adequate to describe such processes will be very complex, if indeed a totally satisfactory model is ever developed.

We believe that remote sensing techniques have their greatest actual and potential application in studies related to SIP development and revision. We

will show how two existing remote sensing tools have application in such work: The airborne earth-reflected differential absorption device for measurement of ozone and sulfur dioxide and the down-looking LIDAR for determining plume dispersion characteristics.

EARTH REFLECTED DIFFERENTIAL ABSORPTION SYSTEM

One of the goals of many researchers working throughout the country has been the development of pollutant-specific remote monitoring instrumentation. Active systems, those using an interrogating signal, depend on the differential absorption of light from two or more chosen laser frequencies. Two different basic classes of instruments are those instruments which use retroreflectors and those which use topographic targets or aerosols as reflectors. One such device under study is a system designed to measure ozone from an airborne platform; this system uses the ground as a reflector. The system has been designed and constructed by the EPA and is currently being flight tested. The operational principles are straight forward. Two lasers are fired sequentially about 15-nanoseconds apart toward the earth. The short period between the separate laser pulses ensures that the beams hit essentially the same spot on the ground and traverse the same path through the air. The lasers operate in the 10 micron infrared region with one frequency located on an absorption band of ozone and one just off the band.

Both reflected signals are received with a common telescope and detector and both lasers are monitored for output power. If the return signals are normalized against their respective values for power output, the only difference in the return signal will essentially be due to ozone absorption. Note that the device monitors the total amount of ozone beneath the aircraft. To estimate concentrations some knowledge of the spatial distribution of the ozone is necessary. Results of ground tests confirm a predicted sensitivity of 8 parts per billion ozone in a 1-kilometer column with little interference from other gases.

The differential absorption ozone device will be used in a special monitoring study of the previously mentioned oxidant/precursor transport problem. Oxidant or oxidant precursor transport over large distances has been demonstrated in previous studies.(5) In order to develop appropriate control strategies, the actual magnitude of the impact of the transported oxidant and/or precursors must be quantified, and if possible, a model developed to relate emissions to their distant impact. The earth-reflected differential absorption device can be used to establish ozone fluxes from one area to another, a measurement which can only be approximated by other methods. Accurate measurement of ozone fluxes will greatly advance the quantitative understanding of oxidant transport. A similar system using two laser lines in the ultraviolet range near 300 nanometers shows potential as a device for monitoring sulfur dioxide. Laboratory tests and calculations favor this approach over a device operating in the infrared regions.

AIRBORNE DOWN-LOOKING LIDAR

The second technique we wish to consider is the down-looking airborne LIDAR in the specific application of determining plume dispersion characteristics.(6) The device used here was also constructed by the EPA and is operational. A short, 300-nanoseconds pulse from a flashlamp-pumped dye laser is fired from the aircraft towards the ground. The beam is scattered by molecules and aerosols within the atmosphere, and eventually is reflected from the ground itself. A small amount of the reflected and scattered light is received by a telescope/receiver system on board the aircraft and a time sequence of the returning signals is recorded. These data are displayed in real time on board the aircraft (Figure 2) and are recorded on digital magnetic tape. In addition, supplemental information including time of day, navigational information, and sequential shot number is recorded on a leader to the LIDAR recorder.

The airborne down-looking LIDAR can be used in SIP modeling studies to measure point source effluent plume parameters. The device, together with its real-time graphic display capabilities, can be used to measure vertical and horizontal plume dispersion coefficients, plume centerline height, and points of

maximum ground level impact. These parameters, particularly the dispersion coefficients, are usually estimated for modeling purposes, thus raising the possibility of large errors. Dispersion coefficients are typically estimated from data collected in small-scale plume dispersion experiments over flat grassy land in Nebraska. (7) Actual measurement of these parameters can considerably improve model accuracy.

COMPLIANCE MONITORING AND OPACITY MEASUREMENTS

An examination of existing reference and equivalent measurement methods for ambient concentrations reveals a total absence of any remote sensing techniques. While this situation will probably change over the years, it is important to realize that, despite their lack of legal status for ambient monitoring, remote sensing techniques can now be used in compliance monitoring by providing information to help design fixed monitoring networks. Remote sensing techniques can be used to site the monitoring stations in the most representative locations and possibly to reduce the total number of required stations. A specific example is the use of LIDAR obtained plume contact data for positioning a ground based air monitoring station.

Another type of remote sensing compliance monitoring which has already found application is opacity measurement. Historically, plume opacity measurements for stationary source emissions have utilized the Ringlemann visual test by a trained observer. Unfortunately, this technique requires daylight. In-stack monitoring with transmissometers (which would be suitable for nighttime use) is often prohibitively expensive. The use of LIDARs to measure opacity would offer both cost advantages and day/night capability. This technique would also allow monitoring of facilities suspected of relaxing control devices at night. The EPA's National Enforcement Investigation Center in Denver, Colorado, has recently procured a van-mounted LIDAR system specifically designed to measure the opacity of point source plumes. The device works by comparing the scattered return signal immediately in front of the given plume with that immediately behind the plume. The ratio of the two signals is a function of the attenuation of the pulse through the plume. The method has been tested using several existing systems and it is hoped that after a suitable testing period, the technique can be applied to this rather difficult compliance monitoring problem.

Simultaneously with the collection of opacity measurements with the new system, correlation data comparing the opacity with plume backscatter values will be obtained. If reasonable correlations are obtained, later devices may be only required to measure the magnitude of the plume backscatter signal. This would obviate the need for the present very powerful visible light laser pulse and enable future systems to use lower power pulses at eye-safe frequencies. In addition, airborne measurements of opacity could be made. Figure 3 is a series of downward-looking LIDAR traces taken on a power plant plume in St. Louis, Missouri, and illustrates some of the difficulties involved in making absorption measurements. The plume is trapped by a temperature inversion, and more scattering is observed beneath the inversion layer. Failure to take this information into account leads to the absurd conclusion that the opacity of the plume is negative. Some corrections could be made using a clear air trace just before the plane flew over the plume, but an accurate measurement would require much greater attenuation by the plume.

PHOTOGRAPHIC MEASUREMENTS

Another remote sensing technique which has been used in a compliance monitoring application is a photographic method for measuring plume opacity. The application is again directed towards compliance emission monitoring. The method can be used only under rather ideal weather and daylight conditions but is extremely cost-effective compared to the use of trained visual observers. Given a reasonably clear day, many industrial sites could be surveyed by one aircraft. The method is essentially a comparison of film densities from the shadow of an opaque object and the shadow of a plume across a surface of constant reflectivity. Such surfaces would include roadways and waterbodies. In its simplest form an aerial photograph is taken containing the shadow of a plume and the shadow of an opaque object on a roadway. Film densities are measured at these

points and on the roadway with no shadow. In the extreme case a plume shadow density equal to that of the shadow of the opaque object would yield an opacity value of 1 with corresponding lesser values with reduced density. A simple equation relates opacity to the actual measured values for density. The method can also be extended to cases where the shadow of the opaque object and the plume do not transect the same homogeneous surface. The second method in practice gives rise to a much greater number of possible measurements.

CONCLUSION

A number of current remote sensing techniques are finding application in the several classes of monitoring needs of the U.S. Environmental Protection Agency. At the present time, remote sensing techniques appear to find their greatest application in SIP development studies. In addition, active research by many groups continues on a wide variety of remote sensing systems with most effort concentrated on pollutant-specific active systems. Future monitoring needs will require an increasingly more involved role for remote sensing techniques in air pollution monitoring if monitoring is to be cost effective and is to provide the oftentimes necessary synoptic view.

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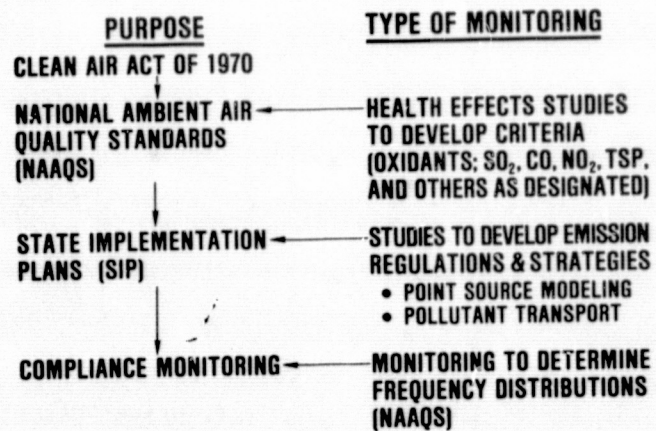


FIGURE 1. RELATIONSHIP OF MONITORING TO AIR QUALITY RESEARCH.

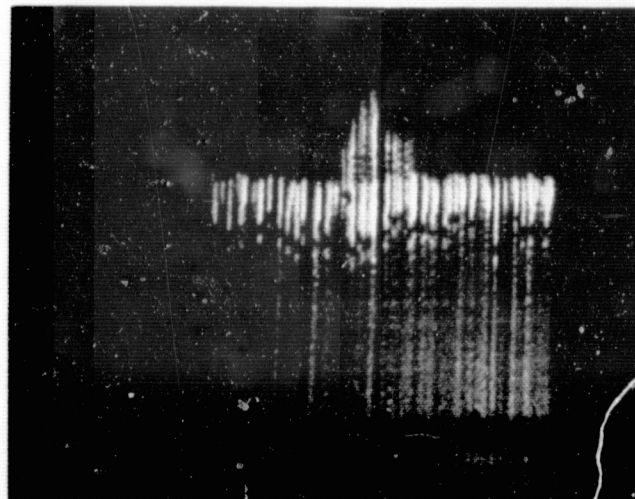


FIGURE 2. PHOTOGRAPH OF REAL TIME LIDAR DISPLAY. Photograph shows plume rising 1800 feet above ground surface. Horizontal dimension of photograph is approximately 3 miles.

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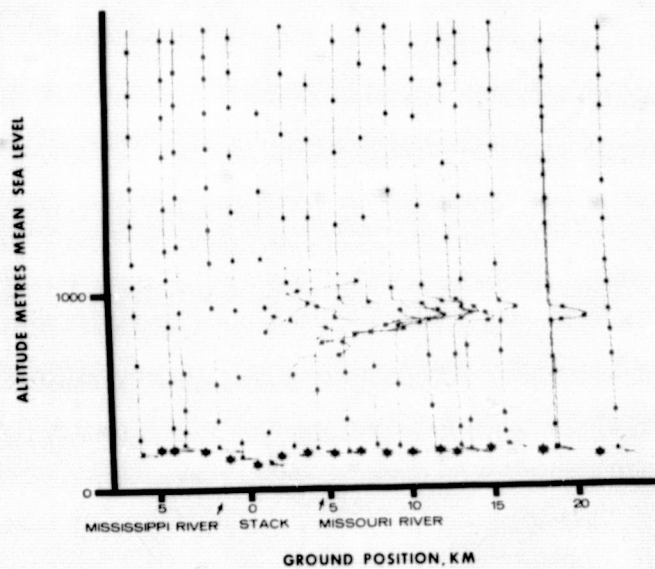


FIGURE 3. LIDAR RETURNS FROM POWER PLANT LOCATED NEAR ST. LOUIS.
Flight traverse passes directly over plant, continuing downwind.

OMIT

REMOTE SENSING OF WATER POLLUTION

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SUMMARY

Remote sensing of water pollution is of interest to determine sources of pollution, movement of pollutants after their introduction into water and, if possible, the identity and quantity of the pollutant. Remote sensors on aircraft or spacecraft can cover large areas in short periods of time, but a number of problems are encountered in such observations.

The most pressing problem is that of the contribution of backscattered sunlight from the atmosphere to the signal observed at any reasonable altitude that will allow wide area coverage. Water penetration is low in the near infrared, so measurements of reflected sunlight are conducted in the range from 450 to 1100 nanometers, a spectral interval with intense scattering. The result is that the sunlight reflected from material in water usually accounts for only 10 to 20 percent of the signal observed by aircraft or spacecraft.

Another problem is sun glint, specular reflection of sunlight from wave surfaces. Glint can saturate a sensor with dynamic range set to accommodate diffuse reflectance from material in the water and the atmosphere or mask the color caused by subsurface scattering to the point where all water content information is lost.

Glint can be avoided by careful selection of flight times and flight lines in aircraft experiments, or by tilting the direction of scan away from the sun as will be done on the Nimbus G Coastal Zone Color Scanner. Atmospheric backscatter cannot be avoided, so provisions must be made to work around it. Sensors must be made with sufficiently high signal to noise ratios so that the "useful" signal to noise ratio, representing only 10 to 20 percent of the total, is still adequate for the desired analysis. Measurements to date show that a total signal to noise ratio of 150 to 1 is needed at the blue end of the visible with slightly less stringent requirements at longer wavelengths.

All of these problems, and more, were encountered in a remote sensing expedition called MESA (Marine Ecosystems Analysis) in one of the most polluted areas on our coastline, the New York Bight. The expedition used surface ships and aircraft with sensing from altitudes of 300 meters to 19.8 km.

At low altitudes, spectral measurements showed significant differences in spectral shape between a strongly colored pollutant, the acid waste dump off Sandy Hook, and such things as sewage sludge and the Hudson Plume. The sewage sludge and river plume were different, principally in the magnitude of the scattered signal with very similar spectral character. This is not surprising since both have a very similar brownish color when viewed from low altitude. All of the pollutants scattered more sunlight than clear ocean water at all wavelengths in the low altitude measurements.

A U-2, equipped with a ten-channel Ocean Color Scanner, carried out simultaneous measurements with the low flying aircraft crossing the New York Bight at 19.8 km. The scanner provided spectral information and imagery of the dumps and the river plume. As might be expected, the spectral character of the signal was badly diluted by atmospheric backscatter, but the imagery provided morphological information that was not available from low altitude data. Dumps could be identified by position and shape, supplementing spectral information, and the movement of material from older dumps could be tracked.

A method of analysis was attempted wherein the mean radiance from all parts of the scanner image sensing water was calculated for each spectral band. Deviations from the mean were used to generate characteristic signatures and the signatures tested, to see how well one signature agreed with surface truth over a wide range of total suspended particle and chlorophyll concentration. Good agreement was achieved with total suspended particle measurements, but chlorophyll in the Hudson Plume showed a wide scatter.

The conclusion from the results to date is that remote sensing can provide a reasonably good estimate of total suspended particles in conditions such as a heavily sedimented plume, but that individual constituents, even specific absorbers such as chlorophyll, cannot be adequately quantified when they are not the dominant material in the suspension.

REMOTE SENSING OF ENVIRONMENTAL IMPACT OF LAND USE ACTIVITIES

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ABSTRACT

Aircraft and spacecraft multispectral scanning sensors have increased substantially the capability to monitor land cover over that associated in the past with aerial film cameras and radar systems. A proposed Thematic Mapper with greater spectral and spatial resolutions for the fourth Landsat will usher in new environmental monitoring capability. In addition, continuing improvements in image classification by supervised and unsupervised computer techniques are being operationally verified for discriminating environmental impacts of human activities on the land. The benefits of employing remote sensing for this discrimination as opposed to more traditional ground sampling methodologies have been shown to far outweigh the incremental costs of converting to an aircraft-satellite multistage system. An example of land use monitoring by satellite multispectral scanners for local, large scale urban environmental impact assessments are the Central Atlantic Regional Ecological Test Site (CARETS) by the U.S. Geological Survey. From a regional perspective, the Association of Bay Area Governments (ABAG) in California and the Regional Environmental Assessment Program (REAP) in North Dakota are experimenting with Landsat data in developing environmental data bases, whereas the Pacific Northwest Land Use Task Force and the U.S. Army Corps of Engineers are further along in the technology transfer process by utilizing remote sensing data for the continuous updating of environmental information systems. The Maryland Bureau of Mines and Geology is using Landsat imagery specifically for monitoring total area and land cover change in the state due to strip mining activities.

INTRODUCTION

Sensors and Platforms for Environmental Land Surface Monitoring

Although non-metric framing cameras have proved adequate in the past for environmental land use monitoring, the need for flexibility in image enhancement by digital means, classification, rectification, rapid color rendition of scene data, and computer storage of image data for rapid retrieval and composite overlays with other data sources has resulted in the multispectral scanner becoming the workhorse for environmental planning. The side looking radar (SLAR) and newer synthetic aperture radar (SAR) are very useful for geological structural mapping, soil moisture determination, and ocean wave measurements, but these systems are still far too expensive to be of more than passing interest in operational environmental monitoring.

The earliest satellite Earth Resources surveys were performed in NASA Mercury and Gemini flights (Ref. 1). The cameras used in these missions had resolutions too large for environmental surveys except to drive home to the public the concept of spaceship Earth. The Hasselblad camera, developed on the Gemini flights, became the astronauts' workhorse during the Earth imaging experiments of the Apollo missions. The Landsats 1 and 2, with their 4-band multispectral systems (MSS), became the first true satellite environmental land monitors. Most of the case studies presented in this paper are Landsat applications. Good high resolution, environmental baseline data can possibly be obtained from the S-190A multiband and the S-190B Earth terrain cameras of the three manned Skylab missions. The third Landsat-C to be launched in March, 1978, will have a fifth thermal band (10.5 - 12.6 micrometers) of doubtful use to land environmental problems, but the advent of the Thematic Mapper on Landsat-D (1980) with 6 proposed bands and 30-meter resolution will undoubtedly be an asset to environmental planners. It would seem that the relatively short Shuttle flights with payloads similar to the European Space Agency's (ESA) Spacelab payload would be ideal, intermittent yet periodic monitors of land surface dynamics. NASA is presently planning possible sensor payloads for its own purchased Spacelab to supply an Earth Viewing Applications Laboratory (EVAL) (Ref. 1). There are also various other satellites of more interest to water and air quality applications; e.g., the proposed SEASAT-A, Nimbus G with its Coastal Zone Color Scanner, and all of NOAA's weather satellites.

NASA also has a significant fleet of research oriented aircraft for environmental applications. The NASA Johnson Space Center maintains a Lockheed NP3A (Union) having an airborne multi-spectral photographic system (AMPS) oriented toward oceanographic observations along the coastal zones. The Center also has a Lockheed NC-130 B (Hercules) used extensively to support multidisciplinary studies with a Bendix 24-channel scanner. Their two RB-57F's normally carry either two Zeiss mapping cameras, electrically driven Hasselblads, or the AMPS. Both 57's have experienced structural problems and have been grounded during the last 2 years. The NASA Ames Research Center maintains 2 Lockheed U-2 high altitude research aircraft which carry in combinations the four matched Vinten multispectral cameras, the RC-10 metric mapping cameras, and the HR-732 (Hycon) cameras. There are several other remote sensing aircraft at other NASA Centers and many private aerial mapping companies have their own low to medium altitude aircraft (up to 50,000 feet).

Digital Image Processing and Classification:

Digital image processing and classification have become branches of artificial intelligence and pattern recognition for study in their own right. Image processing generally begins with picture enhancement, consisting, but not limited to, digitizing, magnification, picture averaging, gray scale reduction, histogram analysis, contrast enhancement, spatial filtering, reversing, shifting, rotating, edge enhancement, and other transformations of the image parameters to increase feature information of interest. Image classification then proceeds during which the enhanced image features are partitioned into regions of similar categories. An excellent summary of various image processing systems for one point in time (early 1977), describing industry, university, and NASA research and development as well as investigators' names and addresses, can be found in a soon-to-be published Jet Propulsion Laboratory report by E.T. Johnson and J.V. Lamar called Final Report - Low Cost Data Analysis Systems. Unfortunately, no similar monumental task has been performed for image classification systems.

One statistical approach to image classification is Bayes Decision Theory (Ref. 2). The decision rule is to select a certain class (land use type, for example) with the highest a posteriori probability, calculated by multiplying the conditional probability density functions for the measured surface brightnesses given each class type with the a priori probabilities that the class type exists in the scene. Since the conditional densities are rarely ever known, parameterization techniques are usually employed to obtain the maximum likelihood estimates of the values characterizing the functions (means, covariance). When known surface features are used to train the computer in deriving these parameters, the training is called supervised. If the density functions behave differently than the more commonly known ones, nonparametric techniques such as discriminant analysis or nearest neighbor must be resorted to. If training samples are not available, clustering can be used in an unsupervised mode to gain insight into the land surface brightness structure in designing the supervised classifier or for change detection after a baseline inventory has already been established.

There is presently a proliferation of classifiers operating in the U.S. today. Most universities, industries, and institutes working with digital classification have access to a maximum likelihood classifier, since generally this system achieves highest classification accuracies, howbeit at most cost. An example of a nonparametric, supervised discriminant function classifier is the Sequential Linear Classifier (SLIC) (Ref. 3) of the NASA Marshall Space Flight Center. The Spatial and Spectral Clustering Program (SSCP) (Ref. 3) operates in both the supervised and unsupervised mode, the supervised to build a crude classifier. There are of course hybrid systems which combine unsupervised, nonparametric clustering with determinant functions, such as the Histogram Inspired Neighborhood Discerning Unsupervised (HINDU, Ref. 3) and a Jet Propulsion Laboratory Bayesian technique combined with a Parallelepiped table look up scheme. A Parallelepiped is an n-dimensional abstract figure, the parallel sides of which in each dimension are defined by the ranges of spectral brightnesses sensed for each given land surface type.

As might be expected, several companies, institutes, and universities have integrated image processing and scene classification programs into operational and marketable systems. For example, the Laboratory for Applications of Remote Sensing (LARS) at Purdue University has developed the LARSYS, the NASA Goddard Space Flight Center has their Atmospheric and Oceanographic Information Processing System (AOIPS), Pennsylvania State University has the Office of Remote Sensing of Earth Resources (ORSER) system, the Jet Propulsion Laboratory has the Video Image Communication and Retrieval (VICAR) system, to name a few of the most commonly applied systems. A detailed description of the linkage of the NASA Earth Resources Laboratory's Image Display System and other peripherals such as strip film recorders, as well as costs, can be found in pp. 11-24 of Ref. 4. Six of the widest distributed commercial systems are the

General Electric's Image 100, the Bendix Multispectral Digital Analysis System (MDAS), the Stanford Technology Corporations' System 101, the Electromagnetic Systems Laboratory's Interactive Digital Image Manipulation System (IDIMS), the Comtal Series 9, and the Interpretation Systems Inc. System 470 SAND. All six of these systems, in addition to carrying out standard image enhancement, incorporate supervised and unsupervised classification, mensuration by pixel counting, or binary masks, and other statistical operations such as training field selection, derivation of training field statistics, multispectral/multiclass analysis, and optimum bands selection. An excellent 18-page table listing detailed capabilities of these 6 systems has been prepared by V.P. Carter, F.C. Billingsley, and J.V. Lamar and will appear in a soon-to-be published U.S. Geological Survey Professional Paper. The table also will appear in the aforementioned, soon-to-be published JPL report - Low Cost Data Analysis Systems.

Economic Cost - Benefits:

Among the recent proliferation of remote sensing cost/benefit - cost/assessment studies, there are two (Ref. 5,6) dealing exclusively with remote sensing of land use and environmental impact of land use activities, one by the Earth Satellite Corporation (Earthsat), the second by ECON, Inc. The objective of the Earthsat case study approach was to assess the incremental costs and benefits of environmental management information supplied by a continuing Earth Resources Survey (ERS) mission in the 1977-86 time frame. The general areas of environmental management selected for study were the monitoring of wetlands, disturbed lands, water quality, and air quality. Earthsat estimated \$15 million annual benefits using ERS environmental monitoring techniques.

The ECON study estimated \$30 million of undiscounted 1973 dollars as the annual cost savings accruing from an operational Landsat as a component of a Nationwide Land Cover Information System as compared to an aircraft-only system. ECON used a cost efficiency frontier, wherein the number of images which could be produced by a system of Landsats to provide land use information to a National System is plotted against budget costs to produce that number of images. The cost curve is assumed concave upwards, the benefits curve convex upward. The budget cost where the slopes of the cost and benefit curves are equal (and which also represent the maximum net benefit) is the optimal outlay for the Landsat system. Like Earthsat, ECON does little to quantify these curves, but elects to measure equal capability cost savings that accrue to a "with" Landsat data acquisition over a "without" Landsat data collection system.

CASE STUDIES

Central Atlantic Regional Ecological Test Site (CARETS):

The CARETS program was officially started by the U.S. Geological Survey Geography Program and NASA's Office of Applications in 1970. The broad objective of the program was to assess the value of aircraft remote sensing information and later (starting in 1972) Landsat multispectral imagery to the ecological study of a large region surrounding the Chesapeake Bay. The CARETS is illustrated in Figure 1. It includes the heavily populated central Atlantic metropolitan areas of Philadelphia, Baltimore, Washington, and Norfolk, and takes in the eastern quarter of Virginia, most of Maryland including its Eastern Shore, all of Delaware, the southeastern corner of Pennsylvania, and most of New Jersey. Essentially CARETS contains the Chesapeake and Delaware Bays and all surrounding land areas which significantly impact these Bays. The three major aspects of the CARETS project are the development of an information system, user evaluation program, and an assessment of environmental impact.

Although CARETS is a regional remote sensing program, this paper will deal only with one local, urban component of that program - the environmental impact of land uses in Norfolk, Virginia (Ref. 7). This assessment was performed by remote sensing analyses of land use and analysis of the reasons for its transitions by manual interpretation techniques of land use change and by understanding the impact of these changes on environmental quality.

Table 1 is a generalized land use classification for Norfolk - except for urban and non-forested wetlands, the land use classifications of Landsat imagery by photo interpretive techniques agree precisely with the 1972 aircraft-derived CARETS land use information. These accuracies are far better than accuracies obtained by other Landsat investigators for these categories of land uses and the accuracies reflect the superior understanding of land use relationships on the part of the U.S.G.S. in interpreting the imagery. Generally computer classification improves the accuracies of scattered, small clusters of marshland and urban residential and commercial strip developments, especially in the suburban fringe zone. Hence automatic classification with human, time sharing interface by an image display device can be

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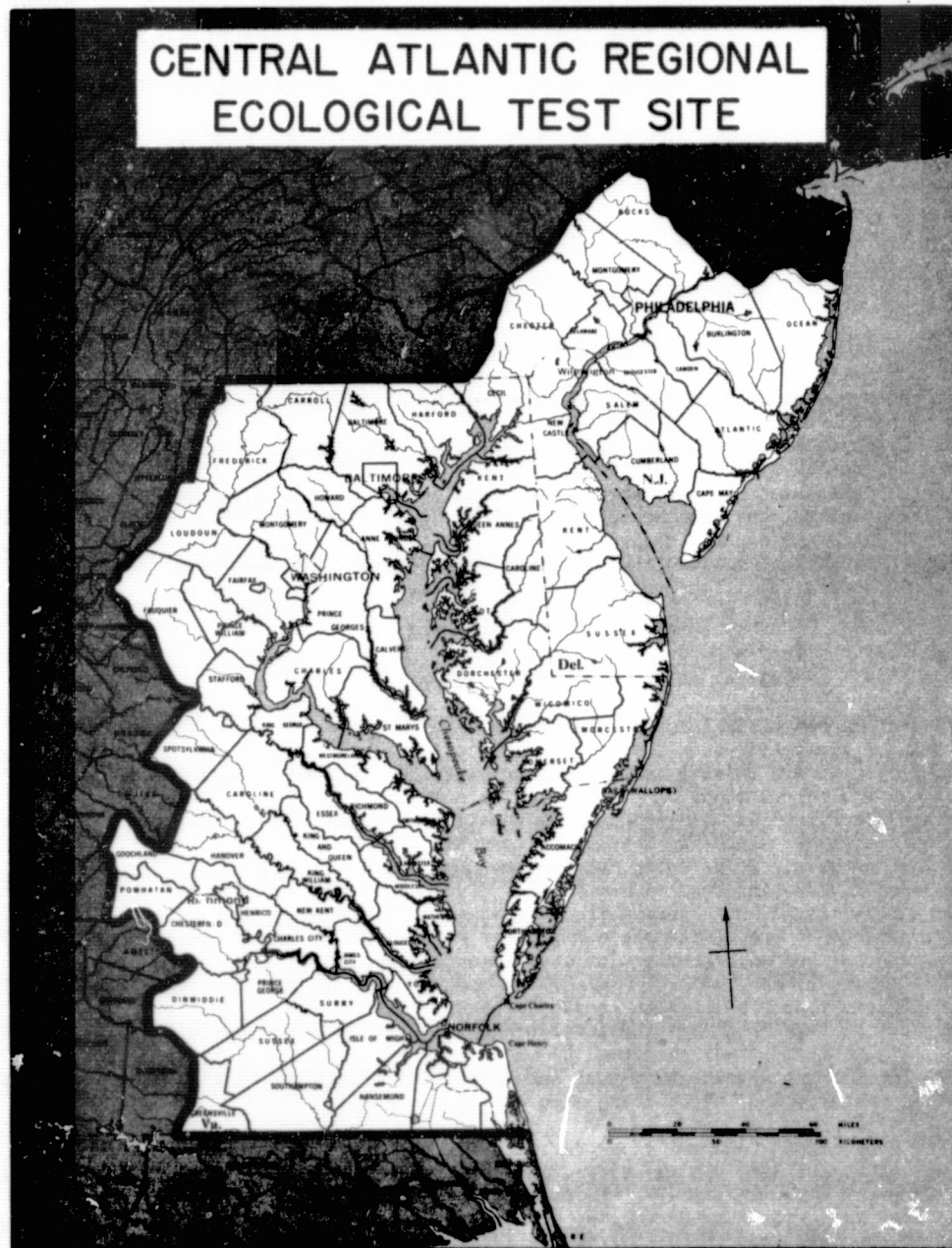


Figure 1.

seen to have tremendous potential advantages in land use classification (for example, see section in this paper on the South Louisiana Environmental Information System).

Table 1. Comparison of 1972 Aircraft* and LANDSAT** Level I Land Use Areas*** for the Norfolk Test Site****

LAND USE	1972 AREA FROM AIRCRAFT DATA INTERPRETATION		1972 AREA FROM LANDSAT DATA INTERPRETATION		LANDSAT ERROR Percent
	Hectares	Acres	Hectares	Acres	
URBAN	43,102	106,505	47,736	117,956	18
AGRICULTURE	48,391	119,574	48,047	118,724	1
FOREST	75,475	186,499	75,136	185,661	0
NONFORESTED WETLANDS	7,802	19,279	5,444	13,452	32
BARREN	1,434	3,543	1,448	3,578	1
TOTAL	176,204	435,400	177,811	439,371	

*1970 CARETS aircraft data area measurements digitized by the Canada Geographic Information System (CGIS) adjusted for 1970-72 Level I change.

**1972 CARETS LANDSAT data area measurements from maps digitized by the CGIS.

***Does not include category 5, water bodies.

****Reprinted from Ref. 7, p. 2-2.

In Table 1, the 1972 aircraft-derived CARETS base was obtained by extrapolation of an initial 1970 aircraft inventory plus a 1970-72 land use time rate of change.* The 1970 inventory was established from 1:120,000 scale, high altitude RB-57 imagery taken during September 22-25, 1970; 1970-72 land use change was extrapolated using this imagery plus another set taken on May 29, 1971. Controlled photo mosaics were constructed from both sets of imagery taken by the 9-inch format, RC-8 camera with 2445 Eastman Kodak Ektachrome Color Aerial Film. Features as small as 15 feet in length on the ground could be identified.

The U.S. Geological Survey did not merely finish their Norfolk task with a land use map; indeed they applied the CARETS 1970 land use map to derive estimated point and area annual emissions of sulfur dioxide (SO₂) (Ref. 8). The emissions were estimated for the winter 1971-72, the entire year 1972, and projected for 1985. The CARETS land use maps were overlaid with 2.5 km grids in the Norfolk-Portsmouth Standard Metropolitan Statistical Area (SMSA) and larger 5 km and 10 km grids in the less urbanized areas to the east and south of the SMSA. Percent of land uses in each cell were calculated and converted to emission rates based on tons emitted per day of various residential, commercial, and industrial use types. The Martin-Tikvart Air Quality Display Model of the Environmental Protection Agency (EPA) was used to project the diffusion and concentrations of the SO₂ and particulates using a slightly modified Gaussian diffusion equation for an elevated, continuously emitting point source. The calculations are adjusted to project long term, average concentrations for multiple point and area sources under a variety of meteorological conditions (Ref. 8).

The results of the Norfolk-Portsmouth air quality modeling is that levels of SO₂ from anticipated residential development and point-source changes are not expected to cause serious deterioration of the region's present air quality, even though SO₂ levels exceeded both primary and secondary levels during the 1971-72 winter. The total 1972 annual levels of particulate matter

*A technique employed in many socio-economic models. For example, many population projection models employ a census base (e.g. 1970) plus a population rate of change based on land use transitions. Census data is also integrated into the CARETS base for selected regions.

regularly exceed primary and secondary standards and by 1985 are projected to exceed presently established secondary air quality standards throughout Norfolk and Portland and even parts of Virginia Beach.

The lack of accurate and detailed land use information has forced the EPA to employ direct emission source control strategies, such as zoning rollback procedures or proportional reductions in regional emissions. The Agency is now planning for Air Quality Maintenance Areas, in which various land use alternatives and strategies for controlling rates of emissions can be considered. Up to date land use change information via remote sensing has been shown by the CARETS program to be an essential ingredient to this program.

The Association of Bay Area Governments (ABAG):

A rather unique and encouraging application of Landsat MSS data to large regional data bases is being initiated by ABAG in its development of an environmental information system. Landsat classified land use information is proposed to be used for calibrating land uses projected by the Planning Land Use Model (PLUM), a substantial component of the information system (Ref. 9). In addition, Landsat data has the potential of providing land cover input information to PLUM, as well as monitoring regional growth via satellite change detection.

ABAG's development is a prime example of how personnel sufficiently motivated toward remote sensing data inputs and with meager budgetary support can utilize generous support from various Landsat processing and government funding sources to piece together an ambitious, yet promising geoprocessing information system. The geoprocessing framework of ABAG's system is termed the Bay Area Spatial Information System (BASIS), one of the few really appropriate acronyms in the geoprocessing/remote sensing business, since the system forms the geodetic basis of all ordinal and even nominal data which enters the system. BASIS codes point, line, and area data to Universal Transverse Mercator (UTM) one-hectare grid cells. Primary data to date are digitized census tract boundaries and 1973 classified Landsat imagery. Data output consists of choropleth, contour, and proximal mapping for line printers and electrostatic plotters, as well as aggregated summary statistics. ABAG pieced together the radius search, area calculation, and overlay modeling software to generate this output through a contract with Environmental Systems Research Institute and a subroutine transfer from Oak Ridge National Laboratory.

ABAG contracted with the University of Kansas Space Technology Center for inputting 17 Landsat-classified land cover types. In addition, with the assistance of the NASA Goddard Space Flight Center (GSFC), ABAG is about to commence remote job entry for Landsat MSS classification with the Office of Remote Sensing of Earth Resources (ORSER) at Pennsylvania State University. This is permitting ABAG to analyze 1976 Landsat imagery through a unique technology transfer process; i.e., GSFC has transferred image processing via ORSER to the City of San Jose which, in turn, is now transferring this processing knowledge to ABAG. The ORSER strategy permits ABAG to perform a raw cluster analysis first with Landsat MSS data, and then to classify the scenes later with supervised techniques to produce a permeability map for input to ABAG's surface runoff modeling effort (Ref. 10).

The capability of regridding Landsat pixels to UTM hectare grid cells, the projection units of BASIS, is being obtained in the form of the Varian-based GEOREF computer software program from NASA's Earth Resources Laboratory in Slidell, Louisiana. This program will also allow ABAG to output ORSER-classified land cover types in hectare grid units. In addition, ABAG plans to formally link its Varian computer with the computer resources of the Lawrence Berkeley Laboratory (LBL) since both LBL and ABAG are interested in sharing Landsat processing and classification software, data compression, and minicomputer optimization techniques.

By phasing into the rather involved analysis using Landsat MSS data through limited NASA support and industry contracts, ABAG appears to have gained considerably in sharing computer support with various private and government institutions and now enjoys an increasingly improved environmental information system.

North Dakota Regional Environmental Assessment Program (REAP):

A large and significant program to assess environmental and demographic impact of natural resource development was adopted by the 1975 North Dakota Legislative Committee in the form of House Bill No. 1004 and signed into law by the Governor on April 10, 1975 (Ref. 11). The law directed the Legislative Council to appoint a Resources Research Committee to be responsible for the development of REAP. The impetus for REAP was the increasing interest in coal extrac-

tion in the southwestern corner of the state and possible resulting environmental and socioeconomic impacts of the land surface alterations. Here again is an illustrative example of potential and real land surface changes prompting the development of statewide, comprehensive, multi-million dollar inventory programs. For the role of remote sensing in monitoring coal-strip mine areas, the reader is referred to the section on Western Maryland Appalachian Strip Mining. In addition, Ref. 12 is an excellent, detailed description of Landsat classification of 30 active, inactive, and proposed coal mine sites in North Dakota, Montana, and Wyoming by the Environmental Protection Agency.

REAP is funded on a biennial basis, with \$2 million provided for 1975-77 by an appropriation from the coal severance tax trust fund. REAP's objectives are to carry out research regarding North Dakota's natural resources, to develop the necessary information systems to address various development alternatives, to assist North Dakota governing agencies in establishing legislation affecting natural resources, to keep the citizens of the State informed of issues affecting resources and the environment, to define the various alternatives in energy development, and to assess their impact. Specifically, REAP is chartered with developing an information base on environmental, economic, and sociological characteristics for North Dakota, designing and implementing a computer-based information system for inputting, manipulating, storing, and outputting this information for use by decision makers, implementing an assessment/modeling system which uses this information system for forecasting the implications of alternative development scenarios on environmental and socioeconomic characteristics, and designing and implementing a monitoring system for baseline information change detection.

In the less than 2 years that REAP has been in existence, it has already moved forward progressively in surveying the research potential of the State in carrying out these objectives and contracting to the Federal Systems Division of the International Business Machines Corporation (IBM/FSD) for the design conceptualization of the REAP system and to the Bendix Corporation for a Landsat-derived land use map of the entire state. In attempting to identify all pertinent data sources for the State, REAP appointed 11 Technical Task Forces in the subject areas of air quality-meteorology, animals, geology, historic archaeological-paleontologic sites, land use, social impact-quality of life, socioeconomic impact, soils, vegetation, water, and noise-radiation-solid waste. A total of 92 technical experts were involved in the State.

One major product to date of REAP is the North Dakota Land Cover Analysis Map Series which establishes the necessary baseline of current land use information. Nineteen Landsat scenes covering the entire State of North Dakota were computer processed to derive the land use maps. Each county was mapped at a scale of 2 miles to the inch and the county maps merged to produce a state map at a scale of about 8 miles to the inch. The maps represent the dominant land cover type for each 1.1 acre covered by one Landsat pixel. REAP is also planning to use the digital classified tapes for composite mapping. In addition to monitoring land use changes in the baseline data, the Map Series will be useful in determining future locations for industrial development projects, transmission lines, and pipelines.

The present status of REAP is that both the REAP Resource Reference System (R³S) and an Economic-Demographic (E-D) model which projects employment and population trends have been developed, are operational, and are being used by the various State agencies. In addition, the Landsat-derived land cover analysis of the entire State has been completed. Two REAP newsletters, INFOCOM for public officials and TECHNOGRAM for technical personnel, are being circulated. The design of the REAP computer system has been completed and approved by the Resources Research Committee, and the 1977 legislative assembly is considering funding the building of the system.

Pacific Northwest Land Resources Inventory:

Three land use urban development projects are significant efforts underway in the NASA/U.S. Geological Survey/Washington/Oregon/Idaho Land Resources Inventory Program. Over one hundred personnel from 35 state and local agencies in this tri-state region have joined NASA and USGS Landsat investigators to pursue forestry, agricultural, and rangeland inventorying, as well as water management and land use planning. A cost effectiveness study has been initiated (Ref.13) to economically evaluate the costs of using remote sensing data in comparison to more traditional methods of acquiring natural resource inventory information.

Information regarding land use impact on the environment is being obtained in the three urban area development studies. The Boise, Idaho, Metropolitan Plan is presently being updated by digital analysis of Landsat data. All vacant lots are being identified as well as the location of all commercial-industrial nodes for transportation planning. Classification of vacant land

is being aggregated to traffic districts and residential land use types are classified according to house density and extent of tree cover. The emphasis in Portland, Oregon, is the determination of impervious areas and wetlands in vacant areas and the location of the urban-rural fringe of the City (for census purposes) and transitional areas where construction is taking place. The Puget Sound and Seattle interests are the urban fringe change detection, location and measurement of disturbed land as input for river basin management modeling and examination of land/water surfaces.

The objectives of all three urban area studies require the transfer of an economical and feasible method of land use change detection to the associated government bodies. A significant step has been taken in this direction by Gaydos (Ref. 14) through "remote" analyzing of remote sensing data. This analyzing is by signature extension of classified land use theme parameters from one Landsat image to another image taken along the same orbital path. In this study Landsat MSS data statistics for land use themes in the Puget Sound, Washington scene were extended to the Portland, Oregon scene, one scene removed, thus eliminating the need for re-training the computer classifier software for land use identification in Portland.

The procedure for the signature extension to Portland is a good example of the many computer processing steps necessary in obtaining a land use product from a Landsat MSS computer compatible tape (CCT). First, the pixel coordinates of the Portland CCT were matched to latitude-longitude by executing a skew transformation existing in the EDITOR computer software on the ARPA network (Advanced Research Projects Agency, Dept. of Defense). The EDITOR software was developed by the Center for Advanced Computation, University of Illinois, and was accessed from the NASA Ames Research Center. The transformed Portland tape was then classified using four channel spectral signatures developed for the Puget Sound, Washington CCT using a maximum decision rule. The Portland, Oregon tape was thereby classified into 37 separate spectral types on the Ames CDC 7600 computer. One 800 bit per inch tape of the classified data was then used to create yet another tape formatted to display the land use themes in 20 colors on the D47 Dicomed Film Recorder. Thus the final land use map of Portland, Oregon, is a combination of various computer processing steps in several different systems and represents much of the latest computer systems development necessary to monitor the land use changes and its effects on the urban environment. The Dicomed color land use map of Portland is shown in figure 2 in black and white. The northerly flowing Willamette River joins the westerly flowing Columbia River where the Columbia turns sharply to the north. The residential light (blue in original) areas of Portland are seen in the narrow region between the Willamette and Columbia Rivers. The commercial and industrial areas of Portland are seen as the darker (red) strips along each bank of the Willamette River south of the junction of the two rivers. The city of Vancouver, with its developing industrial strip on the north bank of the Columbia River, can be seen north of Portland. Other themes discriminated on the original land use map are cropland, pasture, deciduous and evergreen forests, clear vs. sedimented water, nonforested wetlands, quarries, transportation links, and snow.

South Louisiana Environmental Information System:

The South Louisiana Environmental Information System is a joint NASA Earth Resources Laboratory and U.S. Army Corps of Engineers program to produce and update maps/land surface feature classifications using Landsat. A second objective is to specify and document an operational technique covering the necessary hardware, software, and training in order to transfer the remote sensing technology to the Corps for their environmental monitoring of the South Louisiana wetlands.

This program has been underway since 1974, with the first two phases, recently reported on in Ref. 15, now successfully finished and the third phase begun in the Fall of 1976. The first two phases consisted of a demonstration encompassing production of wetland-ecology zone land cover maps for the Corps' Environmental Information System by Landsat MSS digital analysis. As the South Louisiana wetlands represent a very sensitive, yet important ecological resource to the state and the Corps is responsible for management of the Nation's waterways and adjacent land areas as well as for wetlands dredging and alteration permitting, the Corps has decided to enter phase 3 of the program in which they will acquire the ground truth data, select training fields for subsequent computer classification of land cover types from Landsat MSS data, and verify the computer classified results. NASA's Earth Resources Laboratory will provide the hardware and personnel to complete the computer classification products and to train the Corps to take over and operate the satellite-based environmental information system.

In developing this system with the Corps, as well as other systems with the State of Mississippi, the NASA Earth Resources Laboratory has been a leader in the design of low cost,

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Figure 2. Portland, Oregon, Landsat-Derived Land Use Map

flexible digital remote sensing analysis systems. Its support of the Association of Bay Area Government's BASIS has been mentioned in this paper. The six common steps through which they process Landsat magnetic tapes for many of their applications are useful to describe at this point (Ref. 4).

They first reformat the magnetic tapes for their own software system. They next record on color film a raw map of two or three selected MSS bands. Combining this raw map, a 1:250,000 U.S. Geological Survey quadrangle map, and 1:24,000 scale aerial photos, training sites are selected and field teams dispatched to selected areas for ground truth surveys.

The known, ground truthed field sites, with their boundaries subsequently identified in Landsat coordinates by a cursor on the Image Display System, are then inputted to a program which operates on the reformatted raw data provided in the initial step. The raw data windowed by the training field boundaries are statistically processed to define, a priori, occurrences of classes of land cover types and a set of decision tables. The decision tables are then read into the computer and each element (pixel) of the reformatted data tape outside of the training areas are now classified according to the decision tables and displayed on the Image Display System and checked for classification quality.

Ten distinguishable points on the Landsat raw map are colocated on the U.S.C.S. map, such that a Universal Transverse Mercator (UTM) coordinates and Landsat MSS scan line and element number transformation is effected for the classified elements. Finally, the UTM transformed land cover map is recorded with optimal colors for each class on negative color film and the film processed and printed.

An example of a color film product of a land cover map classified by the above procedure is illustrated in Figure 3. Note the extensive non-forested wetlands (marsh) in light tones between the Gulf of Mexico and the higher forested and urban land. The importance of this marshland as a breeding source for fish and wildlife and its cleansing action on industrial wastes can be well understood by this spatial rendition of the total areal extent of this ecologically significant zone. The ability of Landsat to quickly and economically monitor and measure over time the buildup of the urban development patterns (to the North) is a tremendous asset in regulating and controlling urban growth in the Atchafalaya and other river basins of South Louisiana.

Western Maryland Appalachian Strip Mining:

The use of digital classification of Landsat imagery to complement the inventory of Western Maryland strip mines has been successfully demonstrated (Ref. 16) to the Land Reclamation Committee comprised of the State Geological Survey, the Forestry Service, and the Water Resources and Conservation Department. Before 1975, this Committee reviewed permits for coal strip mines based on the Bureau of Mines' inventories of active coal bench surface areas. These traditional inventories are no more than 90 percent accurate in areal disturbance measurements and, due to various degrees of revegetation, generally omit the hard-to-detect orphan mines closed prior to 1967 and the totally affected area. In addition, since the traditional inventories are quite accurate for small mined areas and inaccurate for large mines (whereas Landsat achieves its greater accuracies for larger disturbed areas) and since Landsat is capable of measuring total disturbed surface area including the coal bench, the Bureau of Mines considers Landsat to be ideal for annual strip mine inventories. Since Bureau personnel have extensive knowledge of the locations of coal-bearing formations, some Landsat-generated false alarms (such as road construction, railroad areas, and some urban areas, due to similar signature return) in non-coal producing areas are of no concern to them.

The General Electric IMAGE-100 system was employed to classify four Landsat Multispectral Sensor (MSS) bands using supervised and band-ratio classification training sites (mines) identified on low altitude NASA/Wallops Aircraft imagery. Single parallelepiped training was used in the Georges Creek Basin of the study area, but for the 52 km² test site in Garrett County the band ratio of MSS bands 5 to 6 were compared to predetermined values of this ratio for known strip mined surface reflectances. The resulting classification for

the test site is shown in Figure 4. Three strip mine classes are discernible; class 1 corresponding to exposed subsoil of relatively light color, class 2 denoting open or backfilled mines of darker overburden (producing Pittsburgh coal), and class 3 corresponding to mines having been backfilled and graded, as seen in Figure 5a of the Franklin Hill B mine. The Soil class identifies strip mines already backfilled with spoil, then graded with topsoil. The Revegetated class is illustrated by Figure 5b, a terrestrial photograph of a revegetated section of the Franklin Hill strip mine. The remaining classes of Figure 4 are

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Figure 3. Land Cover Classification Map

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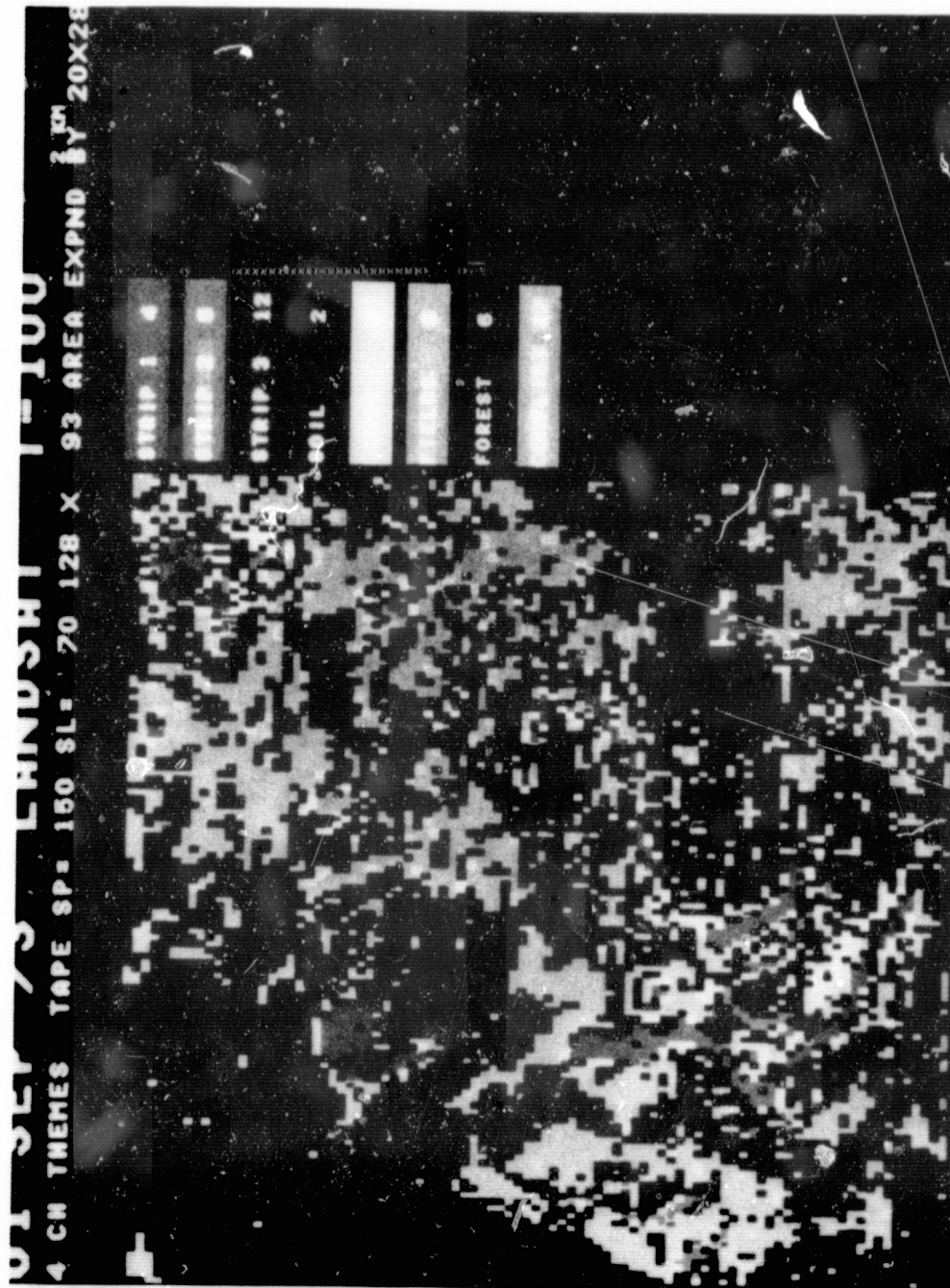


Figure 4. Four Band Classification of Test Site

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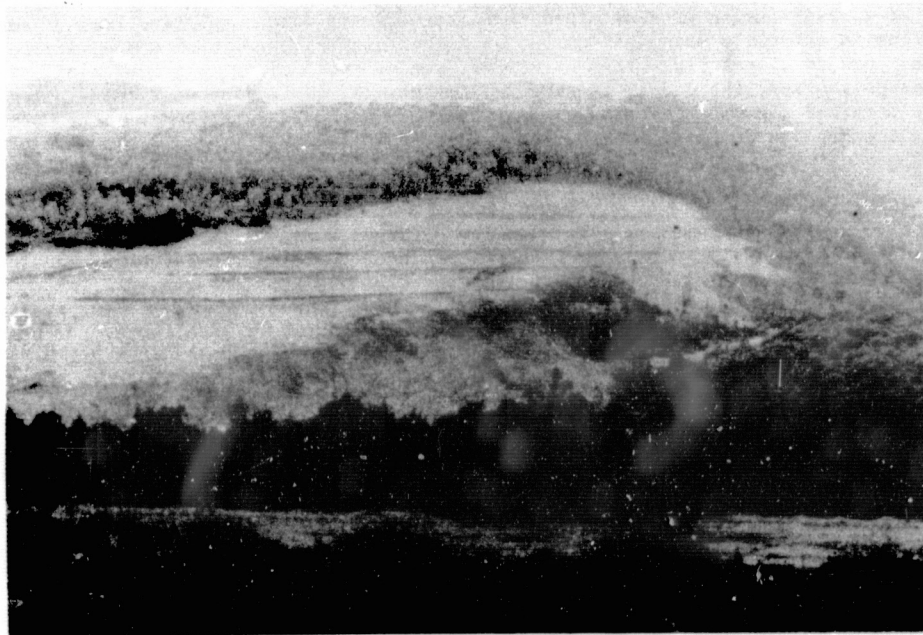


Figure 5a. Backfilled and Graded Franklin Hill Mines

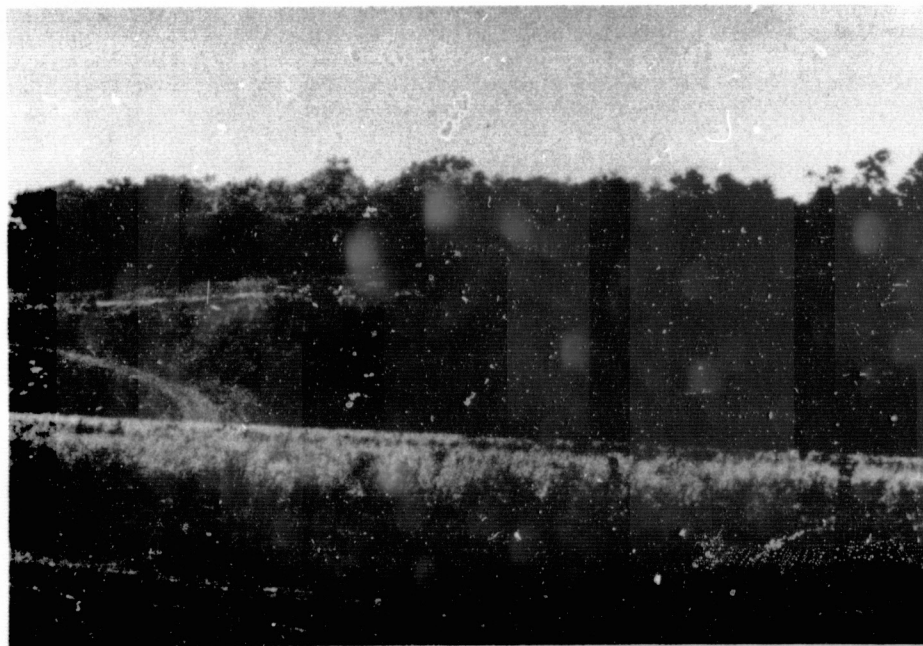


Figure 5b. Revegetated Franklin Hill Strip Mine

fields and forested areas within the region.

Multispectral classification of coal mines in Western states with a relative lack of surrounding vegetation is extremely more difficult than in Western Maryland. For a description of the degree of success in classifying mines as active, graded spoil piles, ungraded spoil piles, and revegetated spoil areas, the reader is referred to Ref. 12. In addition, a description of a later, more detailed aircraft inventory of strip mines in the Western states being carried out by NASA and the EPA can be found in Ref. 15.

CONCLUSIONS

The technical advantages of the utilization of remote sensing satellite and aircraft data to monitor selected cases of land use effects have been documented in these case studies. The Norfolk CARETS studies, as well as others not mentioned in this paper such as Orlando, Florida, reveal a breakthrough in the application of satellite data to map urban land uses meaningful to environmental planners. The Association of Bay Area Governments highlighted the need for satellite data in a large, regional information base. The heavily funded, new North Dakota REAP is incorporating a Landsat-derived land cover map as one of its key ingredients. The Pacific Northwest Region program has shown the continuing, three year requirement of satellite data for urban as well as other land use information. The impact of urban development on the crucial resources of Louisiana's wetlands could probably never have been realized without Landsat's contribution to the Army Corps of Engineer's Environmental Information System. And Landsat's capability in identifying and measuring strip mined areas in the Eastern Appalachian states and, to a more limited extent, in the Western Rocky Mountain states, has been remarkable. Technically, for certain land surface disruptions, remote sensing has proved not only capable of measuring land surface phenomena more economically than conventional methods, but also of measuring a dynamic phenomenon of such great areal extent that no traditional method would ever have been considered for near simultaneous baseline measurements.

ACKNOWLEDGEMENTS

An article which purports to summarize the recent developments in the application of remote sensing technology to environmental land use issues is of course dependent upon the generous communication of the outstanding researchers involved in this application. For their discussions and reports, the author is indebted to the following remote sensing investigators: John Place and James R. Wray of the U. S. Geological Survey, Mitch Modeleski of the Association of Bay Area Governments, A. William Johnson of the North Dakota Regional Environmental Assessment Program, Leonard Gaydos of the U. S. Geological Survey/Pacific Northwest Regional Study, Eugene Zetka of the NASA Earth Resources Laboratory, and Arthur T. Anderson of the NASA Goddard Space Flight Center.

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THE ROLE OF REMOTE SENSING IN THE
BUILDING OF THE INTERSTATE HIGHWAY SYSTEM

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ABSTRACT

It is just over 20 years since the initiation of one of the largest civil works projects in the history of man -- the construction of 68,397 km (42,500 miles) of interstate highways in the United States. Many of the tools used today to locate and design highways were unknown at the time of initiation of this program. This paper presents an overview of the changing role remote sensing has played and continues to play in this vast program.

1. INTRODUCTION

The statement made by Herbert Spencer in 1850 (1, p. 1617:7): "Progress, therefore, is not an accident, but a necessity." succinctly describes the role remote sensing has played in the planning and construction of the National System of Interstate and Defense Highways (popularly called the Interstate Highway System). The Federal-Aid Highway Act of 1956 provided the major impetus for the construction of the Interstate System now totaling 68,397 km (42,500 miles). It provided sufficient funds and the incentive--the Federal Government paying 90 percent of the project's cost--to really get this program moving. Many highway departments faced with the problem of having to handle a vastly increased work program and to rapidly get underway, out of necessity, looked for time-saving and cost-effective tools to aid them in this effort. Remote sensing--or what was then referred to as aerial photographic interpretation--as a result, was more widely incorporated into the highway programs.

The Federal-aid highway program, which includes the Interstate Highway System, is a federally assisted, State administered program. In this relationship, the States retain the initiative in constructing roads while the Federal role is to review and approve the work done with the assistance of Federal funds. In evaluating the use of remote sensing in this program, it is necessary to review the efforts of all 50 State highway departments and the District of Columbia, each one acting as an individual entity in this large program. The techniques applied by one highway organization does not necessarily mean that they are similarly applied by the others. Additionally, many of the highway organizations have used consultants for some of their work with the result that the use of remote sensing techniques varied from one job to another. Consequently, the attempt in this paper is to show a composite picture of where remote sensing is applied, how its use has grown over the years, and how its role has changed as new systems and techniques have become available.

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2. THE CHANGING ROLE OF REMOTE SENSING

(1956): The value of remote sensing to highway engineering had been demonstrated for at least 15 years at the time of the major acceleration of the Interstate program in 1956. The use of aerial photographic interpretation techniques for performing drainage studies, route location surveys, soils investigations and locating construction materials was well documented. The use of this technique by highway organizations at this time, however, was not very extensive. A survey of highway organizations¹ performed in 1955-56 (2) indicated that 33 highway organizations used remote sensing in some phases of their work; but a detailed analysis indicated only 10 were using it fairly extensively.

(Early 1960's): As the Interstate program gained momentum and the State organizations expanded their staffs to handle the increased workload, the States also increased their use of newer and more efficient techniques such as remote sensing, photogrammetry and computer technology. In an analysis of three surveys of highway organizations performed during the period 1961-63 (3), 50 of the 53 organizations reported that they were making use of remote sensing, with 22 indicating a fairly extensive use in some phases of their work. The most extensive areas of use were those previously demonstrated as effective: route location, soils investigations, drainage studies and location of construction materials. In addition, other areas where remote sensing was being applied by the more progressive highway organizations included: highway planning studies, traffic surveys, condition and inventory surveys, construction surveys, and maintenance surveys. Some also applied remote sensing techniques in special studies such as archeological investigations, right-of-way evaluation, and land use surveys. Use was also made of the photographs as an historical record depicting existing conditions and changes occurring over given periods of time. In this time frame, there were also some investigations into the value of aerial color photography for engineering applications. The results of these studies indicated that color photography was better than black-and-white photography for the interpretation of engineering data (4).

(Late 1960's): In the late 1960's, investigations were initiated to evaluate the potential application of the newer remote sensing systems for highway engineering projects. The systems evaluated included various aerial film-filter combinations, multispectral and multiband systems, and infrared and microwave systems (5). Investigations into the use of computer techniques to aid in evaluating and enhancing the data obtained by these various systems were also performed (6). Conclusions from these early investigations indicated that color aerial photography was the best single sensor system for engineering applications; the multispectral and thermal infrared systems and computer techniques were not cost effective for normal engineering projects, but they did offer some unique advantages which warranted further study. As a result of these and earlier studies, the use of color photography by highway organizations increased. Further research into the use of these other sensor systems and into computer analysis techniques was continued.

(Early 1970's): The enactment of the National Environmental Policy Act of 1969 and the Federal-Aid Highway Act of 1970 had a great impact on the highway program. These acts required the preparation of environmental impact studies, and more public involvement in the highway route selection process. This resulted in a great increase in the number of factors to be evaluated, the need for a multidisciplinary approach to evaluate some of the factors, and necessitated an improvement in procedures to present this information at public meetings. Although these laws and subsequent directives outlined the factors to be evaluated, they did not provide guidelines on the methodologies to be applied. They did, however, provide a fertile field for the application of remote sensing techniques and computer technology.

¹In this and subsequent survey results reported, 53 highway organizations were surveyed: 50 State highway departments, District of Columbia, Puerto Rico, and the Federal Highway Administration (formerly Bureau of Public Roads).

The States' response to these new requirements was varied. Those States previously making extensive use of remote sensing relied heavily on remote sensing techniques in evaluating a variety of environmental factors. Some developed special methods using remote sensing techniques for depicting sensitive areas such as wetlands and wildlife habitats (7); for evaluating noise-impact and soil-erosion characteristics (8); and for detailing terrain features (soils, geology, topography, drainage) and cultural features (archeology, utilities, land use) (9). In other States where remote sensing was not used extensively, aerial photography was used mainly to provide a view of the areas under investigation. Computer analysis techniques were also used by some States in evaluating various factors in the performance of environmental impact studies. Remote sensing data, or products normally derived from remote sensing data formed the data base for performing the analyses (10).

Two computer techniques were developed at this time for evaluating the esthetic impact of a proposed route. These were perspective views, and photo-montages. They combined the use of photographs or information extracted from photographs in conjunction with computer techniques to present a view of how the proposed road would appear in the natural terrain setting (11). In the perspective view technique, animated movie sequences are developed by computer techniques which show a view of the road as seen from the driver's viewpoint as he proceeds at various speeds. These aid the designers in evaluating the safety and esthetic aspects of the highway prior to the construction of the road. In the photo-montage technique, a computer-generated perspective view of the highway is overlaid on an oblique or vertical photograph of the area. These provide a two-or three-dimensional view of the road before it is constructed. These have proved very useful for public hearings and cost much less to develop than constructing a model of the terrain with the proposed highway included.

The advent of the satellite age of remote sensing commencing from the Apollo flights and proceeding through the Landsat and Skylab phases had little impact on the highway program. Very few highway organizations made use of satellite data in their programs, and these were generally limited to regional studies. The major drawback to the use of satellite images most often reported was the lack of detail present. Many important details which could be interpreted from the larger scale photography were below the resolution capabilities of the satellite imagery.

(1975-77); The most recent survey of highway organizations was performed in 1974 (12).^{2/} This survey showed very little change in the number of highway organizations using remote sensing over those last surveyed in 1963. All State highway organizations were using remote sensing in some phase of their work, while 23 (compared to 22 previously) were using it fairly extensively. Some of the differences noted in the recent survey were: (a) more States were making use of color photography; (b) remote sensing was used to a greater extent for traffic surveys and right-of-way appraisal; and (c) the newer areas of application reported were preparing environmental reports, use in public hearings, and inventorying roadway conditions.

In recent years, emphasis in the Interstate program has been shifting from new location to maintenance of the system. Most of the Interstate System has been completed or designed: 89.9 percent is open to traffic, 4.3 percent is under construction, and for another 4.2 percent, the location has been approved; of the remaining 1.6 percent, no location action has been taken on only 0.8 percent (13). Yet, it is reported that 37 percent of the total cost of the Interstate is still to be funded (13). This remaining cost is largely for safety and other improvements needed on the existing sections. A system which has been used extensively to inventory the conditions of the pavement and appurtenances to the highway is photologging. Photologging is a ground surveying technique and involves the taking of sequential photographs of the highway and the roadside from a moving vehicle by a camera mounted in the vehicle. The sequential photographs are taken at equal increments of distance (14). Approximately 30 State highway organizations are using this technique. A few States use data collected by aerial surveys for inventorying and evaluating maintenance needs.

^{2/}Some of the conclusions reported in this paper which are based on the 1974 survey were not included in the published summary referenced. They were obtained from the individual responses to the questionnaire.

3. CONCLUSIONS

The use of remote sensing by highway organizations has grown significantly in the past 20 years: in 1956, 33 of 53 highway organizations reported using remote sensing, 10 extensively; by 1974, all were using remote sensing, 23 extensively. It has played an important role in the Interstate highway program. Its role, however, has varied from State to State. A composite view of some of the many ways remote sensing has been applied in the highway field is best obtained by reviewing Chapter 24 of the Manual of Remote Sensing (15). Numerous case studies and examples are included in that chapter.

The highway field, although slow in adopting new techniques, has generally kept pace with the development of new systems and techniques. Color photography, both natural and infrared, is being used routinely by many highway organizations. Multispectral and infrared imagery has been applied in a few specific studies, but has been extensively researched (16). The use of computer analyses in conjunction with remote sensing techniques has been utilized in a few areas --perspective views and photo-montage--but here also, extensive research investigations have been undertaken.

The rate at which new remote sensing techniques are applied can be related to three basic factors. First, are they cost effective? If they do not provide the same information for less, or more information at the same cost as the techniques being used, they will not be applied. Second, upper management needs to make the decision to implement these techniques. There have been many cases where cost effective techniques were not adopted until there was a change in upper management. Third, for success in these techniques, it is important to have trained and qualified interpreters. Since a large part of remote sensing is an art, nothing can discourage the use of a new technique more than an unsuccessful attempt at application by unqualified persons.

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REMOTE MONITORING
AND
TENNESSEE VALLEY AUTHORITY PROGRAMS

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ABSTRACT

In 1933 the Tennessee Valley Authority was created as a resource development agency and charged with the basic mission of improving the economy of a depressed region. To accomplish this, three tasks were identified as part of the original act: power production; flood control, and navigation.

The purpose of this paper is to examine some of those programs that either directly or indirectly support the above-stated mission and tasks and avail themselves of remotely monitored data.

Because TVA is an agency that has operational charges, the chief determinant in any decision to use one method of data gathering over another is its cost-effectiveness. Some programs will be identified as using remote sensing techniques while others are still in the investigative stages and still others have examined some and determined that such is ineffective. This paper will deal chiefly with the first two situations.

1. INTRODUCTION

The Tennessee Valley Authority (TVA) was created in 1933 to help solve the resource development problems of a depressed region. This was the first time that related parts of resource development--flood control, navigation, power production, and other activities--had been brought together in one unified effort for a major region. It represented an effort to look at the "big picture."

From this revolutionary inaugural, it is not hard to understand why TVA is willing to tackle investigations into possible applications of remote sensing for data gathering in local and regional instances. It is the purpose of the following to explain TVA's programs in surveying, mapping, and related efforts in general, and in particular, its involvement in the field of remote sensing.

Initially this paper will deal with the historical aspect of the above-mentioned activities, followed by a discussion of the current organization and functions of TVA's Mapping Services Branch. Then the discussion will center on remote sensing efforts and services provided for other TVA programs, as well as products and services that are available to the public.

2. BACKGROUND

During the early 1930's, TVA and the United States Geological Survey (USGS) were charged jointly with the planimetric mapping of the Tennessee River watershed, and photogrammetric methods were used in carrying out this assignment.

It is interesting to note that aerial photography used to supplement the planimetric map effort was also used by TVA in its rural land classification program. The program undertaken in 1935 was an effort to classify land in the Tennessee Valley into five categories on the basis of those economic conditions of the people and physical conditions of the land that could be observed in the field. All of the field data was recorded on multiple-lens aerial mosaics on a scale of 1:24,000. The field surveys were particularly useful in areas where there was not readily available data on land resources and settlement patterns. This represents one of the first comprehensive efforts to classify the land use.

The planimetric mapping program was initially accomplished by ground-based planimetric methods, supplemented by analyses of aerial photography obtained from a five lens camera. The photo analysis allowed interpreters to differentiate between the main features delineated on the planimetric maps--cultural regions, drainage patterns, and forested areas. The two agencies accomplished the planimetric mapping of the entire Tennessee Valley in 7-1/2-minute quadrangles at 1:24,000 scale in 1937.

In 1936, however, TVA cooperated with the USGS in testing and proving the feasibility of the multiplex stereo plotter as a means of producing standard topographic maps more economically than ground methods. These tests led to adoption of the stereo plotting method in TVA's mapping program two years later. The multiplex is an optical plotter which allows one to compile a map in the vertical dimension, as well as the horizontal. Its use requires two overlapping and nearly vertical aerial photos which, when properly oriented in the plotter, allow the operator to create a three-dimensional model and ultimately a topographic map.

TVA and USGS cooperated in such Tennessee Valley mapping efforts until 1950 when TVA was made solely responsible for topographic mapping activities in the Tennessee Valley. The USGS retained similar responsibility for the remainder of the United States with the exception of coastal regions and certain militarily significant sectors.

The TVA mapping program has continued with improved cameras and stereo plotting instruments under the direction of the Mapping Services Branch of the agency's Division of Water Management. Today's charges consist of updating existing Tennessee Valley topographic maps (7-1/2-minute quadrangles) and creating new maps for use both inside and in some cases outside TVA.

3. MAPPING SERVICES BRANCH OF TVA

Mapping Services Branch provides services to requesting TVA programs and in selected cases, to outside agencies or the public. Administratively, the branch is substructured into sections according to the following basic functions:

1. Photogrammetry and Remote Sensing Section
2. Archaeology, Cemetery and Utility Relocation Section
3. Cartographic and Land Approvals Section
4. Administrative Services Section
5. Map Information, Records and Reprographics Section

The following discussion will briefly outline the basic functions corresponding to the above-listed sections.

The Photogrammetry and Remote Sensing Section is charged with acquiring, processing, and distributing black and white, black and white infrared, color and color infrared mapping aerial photography, as well as that obtained by 70 mm cameras. This section is also capable of flying airborne thermal missions.

Because its mission is oriented toward the aerial acquisition of data, the section is further charged with the duty of coordinating all remote sensing efforts within TVA and acting as liaison between TVA and cooperating agencies and organizations in similar endeavors. All of these efforts will be discussed in greater detail in the next section.

Once mapping photography has been acquired, the section's duties extend to the compilation of topography according to requested specifications. Services are also available for digitizing data in two or three dimensions.

Other services provided by the branch include the coordination for the relocation of utilities affected by construction projects and the coordination and monitoring of archaeological investigations required by law prior to the construction of TVA projects.

The branch performs work involving studies of land patterns and ownership as they relate to program needs, reviews land maps along with field investigations to determine and establish the most logical limits for acquisition, transfer, or sale of land or landrights, together with the preparation of approval forms and legal descriptions necessary to complete the transactions.

The branch is also responsible for providing cartographic services required for lithographic or photographic reproduction of maps, charts, graphs of a widely varied nature and format. These products include topographic, geologic, hydrographic, soils, magnetic, area, project, recreational, survey control maps and/or charts. Some of these products are available to the public by contacting Mapping Services Branch, 200 Haney Building, Tennessee Valley Authority, Chattanooga, Tennessee 37401.

Time and space limit the presentation of detailed discussions on all of the above matters. However, a closer look at Mapping Services Branch responsibility and capability in remote sensing follows.

4. REMOTE SENSING

As previously stated, the duty of coordinating all remote sensing efforts within TVA has been delegated to the Mapping Services Branch. This branch works directly with TVA interests that have immediate or potential need for remotely sensed data and acts as TVA's liaison with outside organizations and agencies having similar endeavors.

As such, the branch has developed certain inhouse capabilities which can be applied either as a research tool or to specific projects as suggested or requested by TVA programs.

One of the first charges of TVA was that of topographic mapping. As a result of this the Mapping Services Branch began obtaining aerial photography in the early 1930's. This photography is maintained in Chattanooga and is available to the public. Due to rapid cultural development requiring periodic update of the topographic maps, there is available valuable sequential photographic coverage of some areas of the Tennessee Valley spanning over 40 years.

TVA maintains one remote sensing aircraft (an Aero Commander 680 FL) which is on call to the Mapping Services Branch on a year-round basis.

The branch maintains two aerial camera systems. The first, a Wild RC-8 metric mapping camera with a 6-inch focal length. This camera with a 9-inch format is compatible with the branch's stereo plotting equipment and is used

primarily for obtaining photography for both large- and small-scale mapping. The second system is multispectral, containing from one to four 70 mm Hasselblads. Each camera may be loaded with a different film or filter combination. The cameras are fired simultaneously.

The Mapping Services Branch has a one channel Daedalus thermal scanner. It is used routinely to monitor water temperature around TVA's power plants.

The branch also regularly obtains aerial oblique photography. This photography is used mainly to monitor progress at TVA projects and is obtained from a helicopter.

Because of its history in collecting and providing to users data of all types, in 1973 the branch was further assigned the task of acting as a regional EROS Browse File. As such, all LANDSAT, formerly Earth Resources Technology Satellite (ERTS) imagery in microfilm format is made available to those interested in evaluating the imagery and that may need help in ordering same from the Data Center in Sioux Falls, South Dakota.

The branch, as a regular practice and as an adjunct to the Browse File, collects all high altitude, color and color infrared aerial photography that covers the Tennessee River watershed and makes it available to TVA users, as well as allows its inhouse evaluation by the public.

The Remote Sensing staff has the ability to advise, use, and educate others in the efficient use of remotely sensed data.

In order to present more conveniently TVA's internal and external dealings within the field of remote sensing, the remainder of this paper will be subdivided into subsections, roughly corresponding to those disciplines that commonly use the remote sensing services provided by Mapping Services Branch.

5. FORESTRY

Forestry was probably one of the first--and today possibly one of the biggest--users of remotely sensed data. To make the best use of these data, the forester is knowledgeable on both the geometric and interpretive characteristics of aerial photography.

A county inventory system was conceived in 1942 and implemented in the 1950's which relied on the most recent aerial photography of the country and the Tennessee Valley topographic maps. To update the survey, it is necessary to acquire additional aerial photography for interpretation. This photointerpretation, coupled with the prescribed number of field checks, yielded up-to-date county forest area estimates with a sample precision of about $\pm 1\%$. Concurrent investigations into the use of LANDSAT imagery show potential use of such imagery as an aid in compiling current forest area estimates for mid-cycle projections and in studying the spatial distribution of forest stand characteristics in relation to other resources.

Aerial photography was also used to locate and aid in the digitization of county lines and to determine water and open acreages. In the mid-1960's, a system of identifying wildlife habitat based chiefly on aerial photointerpretation was initiated.

TVA foresters are charged with monitoring both strip mine progress and reclamation of all mining operations from which TVA buys coal. This also includes the identification of abandoned surface mines and those mines that may contribute to water quality problems within the Tennessee River watershed. This is currently accomplished using black and white and black and white infrared conventional scale photography. When available, high-altitude aerial photography is also used. Presently, LANDSAT is being evaluated for potential use in the location of both abandoned and active strip mines as well as to monitor the effects of reclamation and revegetation activities.

The forestry land analysis laboratory has conducted demonstration projects where general land cover is needed. Such demonstrations include computer-assisted transmission corridor location and power facilities siting. A geographic reference system is loaded with resource data collected from conventional and high-altitude aerial photography and satellite imagery (where appropriate) as well as data from many other source documents. The basic tool used is the Harvard School of Design created software called IMGRID.

LANDSAT imagery is also being considered as a source for course-level land cover screening tool to aid in the identification and monitoring of potentially critical species habitats.

6. GEOLOGY

High-altitude remote sensing techniques permit the geologist to stand at a sufficient distance to view the macro-geologic structure. Commonly used aerial photographic scales (about 1:24,000 or larger) deny such a perspective. High-altitude color and color infrared photography at scales 1:60,000; 1:120,000; and 1:450,000 have been obtained over selected areas of the Tennessee Valley through the National Aeronautics and Space Administration (NASA). Such imagery is extremely helpful to the geologist for the analysis of land forms and regional geologic structure. In conjunction with TVA's Valley Mapping Program, the agency obtains 1:76,000 scale quad-centered aerial photography for about one-seventh of the Valley per year which is also useful to TVA geologists.

Another concern of TVA and State geologists is monitoring strip mine activity. In this regard, high-altitude photography allows the geologist to locate surface mining; catalogue them as to type and ownership and study variations over time provided such imagery is obtained at regular intervals.

The geologist also uses the high-altitude photography and satellite imagery as an aid in evaluating present and potential power facilities sites. Regional features of structural significance often can be detected that could not be observed during surface studies nor inferred from lower level photography. The power facilities siting efforts have also obtained radar imagery which was made into a mosaic and used in the identification and delineation of linear features at selected proposed power generating sites.

TVA's geologists use a proton precision magnetometer towed behind an aircraft to measure the magnetic variations of the earth's crust. This data is used to create a magnetic map of the Tennessee Valley and portions of adjoining areas and ultimately to delineate areas of potential interest for more detailed mineral exploration. The resultant information is published on 7-1/2-minute quadrangles as part of a cooperative program with selected states of the Tennessee Valley region. Satellite imagery and the bands 5 and 6 winter mosaics created by Mapping Services Branch have also been helpful in geologic mineral resource inventory.

7. WATER RESOURCES

Water quality has been one of TVA's prime concerns for many years. Typically, the bulk of the agency's water quality data gathering is done either through field surveys or through in situ monitors with the results telemetered to a collection station. The in situ monitors can collect data on the temperature, conductivity, dissolved oxygen, turbidity, etc.

TVA has spent considerable time and effort in examining the state of the art of airborne thermal scanning methods of determining water surface temperatures. Such methods, if reliable to $\pm 0.5^{\circ}\text{F}$, would prove to be extremely useful in monitoring thermal effluents from steam and nuclear power plants, particularly in light of State imposed thermal standards.

Mapping Services Branch regularly monitors selected power generating sites using an airborne thermal scanner. Using thermal infrared scanning techniques, selected plants throughout the Tennessee Valley were studied on a twenty-four hour basis. Such imagery is used regularly to depict such aspects as plume shape and direction under varied flow conditions. This, in turn, allows investigators to effectively place in situ sensors to gather the more quantitative information and to check the results of mathematical modeling of the plumes.

One of the many efforts within TVA is to predict the flow for various flood frequencies for ungaged watersheds. In a recent demonstration effort, nine land cover variables were obtained from digital analysis of LANDSAT data, and eleven watershed characteristics were obtained from topographic maps and successfully used in a regression analysis to predict flow volumes. This approach is still in the investigative phases.

8. ENVIRONMENTAL BIOLOGY

Parts of the Tennessee River during the summer months becomes overgrown with watermilfoil. In an effort to monitor and control this problem, the branch provides normal color aerial photography flown at conventional altitudes covering the more vulnerable sites.

Because of the concern over SO₂ emissions from steam plant combustion, an environmental biologist on TVA's staff is attempting to correlate SO₂ emissions with crop stress through airborne multispectral scanners and conventional photography. This is a cooperative investigation with the Environmental Protection Agency.

9. INTERDISCIPLINARY OPERATIONS

The programs listed to this point have all required some interdisciplinary cooperation, but the driving force can usually be identified with one branch. In addition to these, however, TVA has a number of other programs which are directed at an interdisciplinary approach to problem solving and use remote sensing as one of the unifying levers. These efforts incorporate programs already mentioned and some will be examined in the following discourse.

In the power facilities siting process it is necessary to both identify sites and evaluate their potential environmental impact. Aerial photography is used for illustrations in all environmental impact statements. All nuclear projects require a regional land-use product which is commonly derived from high-altitude aerial photography.

As was discussed earlier, land classification by TVA is not new. In the early 1930's mosaics created from the photography of the five-lens camera were used to aid in the delineation of the land categories. More recent efforts make use of much more sophisticated hardware and methods.

TVA's Regional Planning Staff compiles subregional planning and development overviews in cooperation with appropriate State and multi-county regional planning staffs for the Tennessee Valley. Information related to the physical and functional characteristics of the land, including present and projected distribution of uses, is assembled on base maps on a scale of 1:125,000. The use of conventional, high altitude, and in some cases satellite imagery are key ingredients to the compilation of the subregional overview. Findings are being reviewed with appropriate State and district planning staffs in an effort to establish a common framework for coordinating planning and development.

TVA's long and successful history of effective, integrated resource development has been due, in part, to the ability of the agency to acquire adequate information upon which to base decisions. Over a period of 40 years,

vast quantities of potentially valuable information pertaining to the Valley resources have accumulated. Some of these data have been captured in the geographic data bases of TVA's mapping program. Some have been carefully filed by the creators or primary users in diverse systems and locations throughout the organization, and some exist solely in the minds of the agency's personnel.

Meanwhile, the demand for information has sharply risen. Increased demand may be attributed, at least in part, to comprehensive energy planning and emphasis on the nuclear program. The situation is, however, aggravated by Federal and State regulatory agencies, government planning groups, and citizen involvement organizations whose voracious appetites for environmental data have caused an enormous increase in both the volume and diversity of TVA's resource data. Major technical problems in data storage, maintenance, and retrieval have ensued.

It is important for TVA to maintain its historic ability to respond rapidly and effectively with resource data at levels of detail, accuracy, and timeliness which are appropriate to increasingly complex inquiries and requests. This will require accelerated efforts to develop and implement a system for managing data on the basis of geographical area covered, subject, and level of detail.

The concept of a tool for storing geographically located data and effectively drawing from it is not new to the Nation or to TVA. TVA's unique charge (i.e., responsibility for a contiguous region of manageable size) and afforded the agency opportunities to pioneer in this area.

Other Federal agencies, hampered with responsibilities for the entire United States without any real operational base, have encouraged and even financially supported TVA's activities. As a result of early agency efforts, the feasibility of using such tools in a number of diverse projects and situations has been successfully demonstrated. Recently, all the divisions within TVA have committed themselves, in terms of time and personnel, to planning for comprehensive development of a more widely accessible TVA-wide service.

The successful design and implementation of the regional resources information tool requires understanding, not only of regional data collection, analysis, and processing, but also of locational mapping as a base for land-related data and the systematic aspects of handling and using large geographic data files. TVA, perhaps more than any other agency, has this expertise.

TVA is an ideal agency to demonstrate the utility and savings of shared data bases. It is a major data user, has the mandate to demonstrate new approaches to old problems, and it has long experience with data bases used in a wide variety of resource planning activities. Furthermore, TVA's unique regional status affords the opportunity to develop and demonstrate, at less than a national scale, how geographically located information can be obtained, analyzed, and used in complex planning activities related to the Nation's energy problems.

Remotely sensed data will obviously not be the "prime-mover" in the creation of this Regional Resources Information Study (RRIS), but it will represent a key ingredient in the formative stages as well as in the update of appropriate data.

The Mapping Services Branch has been collecting and documenting resource data since TVA's formation and anticipates that it will continue to play such a role.

10. CLOSURE

It would be presumptuous to assume that the foregoing discussion has covered all of TVA's efforts toward using remote sensing. Because remote sensing is, in many cases, a relatively recent arrival on the science scene, its complete acceptance is somewhat hesitant. This is healthy, however, because an operational organization must analyze and reanalyze all programs from a cost-effective vantage point: It is in this light that raw research is weeded from a useful science. The hesitancy, however, is diminishing as more and more cost-effective examples of the use of remote sensing take form.

General questions on this article and TVA programs mentioned may be addressed to:

Mapping Services Branch Chief
200 Haney Building
Tennessee Valley Authority
615-755-2133
FTS: 854-2133

Specific questions relating to the EROS Browse File, image acquisition, stereo compilation, etc., may be addressed as above or reached at 615-755-2148 (FTS: 854-2148).

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CORPS OF ENGINEERS APPLICATIONS FOR REMOTE SENSING OF THE ENVIRONMENT

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ABSTRACT

An objective overview is presented of the application of remote sensing technology in the Corps of Engineers. Examples are given of attempts to use the current state-of-the-art to achieve particular disciplinary or mission-oriented goals. The Corps, presently engaged in both research and development and technology transfer, has encountered some interesting situations. Practical operational utilization depends not only on technology, but also economic benefit/cost factors and some unprecedented legal, political, and social issues. Yet, at a time when increased agency commitment to operational usage is being sought, an assessment of the state-of-the-art reveals that sensor technology, data processing and analysis, and models still require further development. There is a challenge in synchronizing technology push with the demand pull of dimly perceived user needs. They should complement each other rather than oppose. The goal is to use the combined push-pull effect to lead to increased productivity and responsiveness by the Corps.

INTRODUCTION

The purpose of this paper is to present an objective overview of the transfer and application of remote sensing technology in the Corps of Engineers. The Corps is actively involved in transferring remote sensing technology from the laboratories to our operating districts. The districts throughout the United States are now applying techniques previously demonstrated with laboratory participation and funding support from the National Aeronautics and Space Administration (NASA) and the Office Chief of Engineers (OCE). The districts are now also developing new applications in a variety of mission areas, some of which are described later.

In the Corps, practical operational use of remote sensing depends not only on what is technically possible and operationally feasible, but also upon the total economic benefit/cost factors and some unprecedented legal, political, and social issues. The latter are increasing in complexity as the Corps is assigned increasing responsibilities in regulatory areas.

To make best use of certain state-of-the-art technology, the Corps has identified certain additional developmental needs at the end of the paper. The scope of the paper is mostly concerned with six areas of application with examples. The areas include hazards assessment and project planning, flood plain analysis, coastal protection, dam safety, operations and maintenance of completed projects, and the regulatory program. The applications have come about through intensive applications of some elements of the process of technology transfer. Thus, this process will be described first so that one can better appreciate why we are where we are today.

USE OF TECHNOLOGY TRANSFER TO DEVELOP APPLICATIONS

The Corps of Engineers has many difficult tasks that require application of improved technology if we can benefit from it, and afford it. For many years photography has been a standard tool used by engineers involved in planning construction projects. More recently engineers have begun to apply, as a policy, multidisciplinary analysis to photo-interpretation to gain further synergistic advantages and cost savings. Generally, the contribution of an interdisciplinary group has been greater than the sum of the efforts of the individuals had they worked alone.

Interdisciplinary analysis is a labor intensive effort which has value, but it also takes valuable time from people with other duties. It even may be disruptive because it is difficult to assemble and operate teams whose members have concurrent demands on their time. Thus, the Corps of Engineers has taken interest when R&D agencies began to develop means that could possibly minimize the total amount of time needed to extract useful information from photographs. The technology might include automated assists in classification, change detection, and ways to minimize the number of photographs which required examination. In addition, recent advances in multi-spectral and multi-temporal coverage offered promise when our engineers were tasked to do additional studies required in the public interest to assess the consequences of man's changing of the environment.

The Corps of Engineers must now learn how best to exploit the newer technology and at the same time broaden its scope of interest. In brief, we must find a way to use the process of technology transfer to develop useful applications of advanced technology that will either reduce our costs and time or provide increased benefit from the efforts we can apply. Adding to this challenge is the fact that most of our work is done by contract. Thus, the process we seek must also eventually place the technology in the hands of A-E firms and the construction industry in such a form that our contractors have the motivation needed to use the new tools. We are now training our people in the districts so that they will know the kind of services to seek from a contractor.

Mr. Robert Frost, our remote sensing consultant at the Engineer Topographic Laboratories (ETL), has conducted 32 training courses over the past 10 years to help over 650 people in the Corps, and others outside the Corps on whom we depend, learn the techniques of multidisciplinary image analysis to obtain information about the environment. The students get hands-on training and work together as a team to produce useful studies on actual projects. Today many of the graduates are actively involved in making practical use of remote sensing of the environment. However, their continuing involvement is due more to management interest than to training, albeit training has been absolutely necessary.

To obtain the management interest we had to go back to basics and study the process of technology transfer. There must be a need looking for a solution. There must be interest on the part of the person with the problem in trying a new solution. Multidisciplinary training is most effective when applied to generate interest and provide hands-on experience working with new tools in the solution of a problem. Often overlooked by technologists is the fact that new methods stand little chance of adoption without strong management action to generate the top-down interest which results in permission for the workers to innovate. Management dedication is also needed to provide resources because the introduction of new procedures may entail additional manhours and expenditures initially. Finally, there must be incentive, some kind of perceived reward, for those persons who initiate change, and those managers who encourage it.

Professionals in technology transfer have shown that all elements of the process must be present if it is to occur at a given point in time. This may create the appearance of a "chicken and egg problem," compounded with possible inertia or resistance to change in a conservative engineering environment. In the Corps we took four specific actions to start the process.

First, we arranged for the Chief of Engineers to identify the promise of remote sensing to his top subordinates who in turn could share this interest down the management chain to the worker. The Chief applauded the initiative of one of his division engineers for making practical use of remote sensing. This introduced something akin to peer pressure as other division engineers were challenged to make their own operational use of remote sensing methods to obtain benefits, such as:

- more complete consideration of alternatives at early stages of plan formulation.
- increased coordination over intervals of time.
- more complete assessment of existing conditions.
- quicker and less costly data collection.
- more effective presentation of the Corps' decisions at public hearings.

Second, to help overcome any perceived inertia the Chief tasked his own staff to develop a plan for increasing the operational use of remote sensing and applying the traditional multidisciplinary analysis procedures of the Corps to photo-interpretation. This planning institutionalized certain longer term considerations and encouraged initiatives that might:

- show which kind of projects can benefit most.
- identify the stage of planning and/or design at which the greatest benefit accrues.
- identify the source of personnel for analysis teams and contractors for additional support.
- show which elements of analysis are amenable to contracting.

Third, the Director of Civil Works in OCE authorized the use of demonstrations, funded by the recipients of the technology, to facilitate operational use of remote sensing and interdisciplinary analysis in the Corps. This, in essence, identified the resources and granted the permission, two of the elements needed in the process. Three major demonstrations have been held to date with division funding. This is in addition to continuing Applications Systems Verification and Transfer (ASVT) efforts funded by NASA and OCE and others due to laboratory initiatives. The objectives of the Corps' demonstrations were to:

- demonstrate and document the application of multidisciplinary image analysis to planning and development of Civil Works projects at division and district level.
- provide continued training in the methods used.

Fourth, ETL initiated publication of TECH-TRAN, an information exchange bulletin which was written for the managers of the process. This bulletin describes details of the process, identifies possible new solutions to problems previously identified within the Corps, and publicizes the initiatives of people in the field who have decided to be pioneers. It also describes the activities of OCE opinion leaders and the Chief's policy statements. In other words, TECH-TRAN is a means of communication which stresses the need for all elements of the process to be moving at the same time. This makes the question of "chicken or egg" almost academic.

The key to technology transfer is awareness of the process at all levels, but the lock is characterized by the field agency (district) which has tight control over its operating mission. Thus, we should consider who it is that turns the key, starts the process, and keeps the momentum. This person is the "linker."

The linker is the person we seek, preferably from within the user organization who can get things done. The linker is a valuable person. We try to get him identified early in a project and involved in our training to set the examples and be a champion for remote sensing. He also serves the role of guide. Those people, particularly in the laboratories and industry, who may tend to push solutions find that the linker can help them align their efforts and identify the real problems. The linker aligns technology push. The linker also helps to guide the others who are attempting to try to apply new techniques. His leadership transforms a demand into an effective pull on technology. The linker should not be hesitant to get involved himself to set the example. This helps the district align the direction in which it pulls to get the new technology.

In brief, the Corps' linkers are helping to overcome the inertia associated with the transfer of remote sensing technology by aligning both push/pull forces so that they work together and by opening the door to new and better ways to do our job.

AREAS OF APPLICATION

This section describes the kinds of projects amenable to use of multidisciplinary analysis of remote sensing imagery, identifies applications during various stages of a project and presents examples in six mission-related areas of application within the Corps of Engineers.

Types of Projects Which Can Benefit

The following assessment is based on experience gained from a series of demonstrations in which the Corps attempted to use techniques for remote sensing of the environment at various stages in actual projects.

Generally it was found that multidisciplinary photo analysis methods are well adapted to meeting the requirements of the National Environmental Policy Act. In water resource development, knowledge of the environment and its sensitivities is of paramount importance in developing solutions and alternatives. Applicable Corps of Engineers projects include dams and reservoirs, development of a national recreation area, wildlife mitigation, disposal of dredge spoil, location of a major canal, stream bank erosion, acid mine drainage abatement, and damage assessment or monitoring operations. All projects require an assessment of their environmental impact in the local area.

Multidisciplinary photo analysis allows us to make a rapid analysis of a large area in a very short period of time and at low cost. This provides a basis for an initial determination and assessment of such important items as environmental complexity and sensitivities, potential engineering problems and degree of feasibility for project development. It helps to better understand and evaluate projects and potential problem areas in the earliest possible stages of development, often before the point of serious public debate. We can develop alternatives based upon careful consideration of the interplay between existing environmental characteristics, project requirements, projected environmental impact and national policy.

Remote sensing, combined with multidisciplinary analysis, is a powerful tool for locating existing hazardous and potentially dangerous geo-technical problems which may greatly affect project location, cost, or even feasibility. For example, while it is not possible to predict such major catastrophic events such as earthquakes, land slides, avalanches, or floods based upon photo methods, it is possible to determine their effects. Careful examination of historical photos (often extending back 40 years) makes it possible to trace and evaluate significant changes that have occurred or resulted from geo-technical events. Striking examples are lineament analysis, sudden breaks in topographic continuity, evidences of slope instability, changes in river/flood plain characteristics, evidences of changes in ecosystem dynamics, and evidences that suggest long range weather cycle changes that may be portrayed in vegetation and erosion features.

Kinds of projects not suited to effective application of multidisciplinary photo analysis procedures include those depending primarily upon mensuration - obtaining and utilizing quantitative data. Examples include demographic studies, water quality and quantity, topographic mapping, mass diagrams for earthwork computations, volumetric data in timber and other resources surveys and in those studies in which physical measurements or test results are of paramount importance (durability of aggregates, grain-size distribution, porosity, etc.) In such instances, the use of airphotos merely becomes a guide, suggesting where to obtain samples or where to expect changes in properties. Other techniques, such as photogrammetry and laboratory testing of field samples must be used to obtain the needed data. However, new computer assisted generalized pattern analysis technology offers promise in defining new computer modeling studies with both qualitative and quantitative input.

Application During Various Stages of a Project

Multidisciplinary photo analysis techniques can provide information about the environment useful to varying degrees throughout the entire planning, developmental and operational cycle of a Civil Works project. However, we believe that the techniques should be employed at the earliest possible stages in the planning process if one is to enjoy the greatest benefits.

The chief importance of early involvement lies in the ability to "scope" a project early. This leads to developing a better plan in terms of funds, manpower, and time. Early analysis provides a basis for developing and examining different solutions and alternatives as may be necessary due to changes in public opinion. Early involvement provides a basis for quick reaction or quick response to changing conditions. One may re-examine pertinent parts of the analysis to effect orderly and efficient change in project direction. This can be done with ease if the detailed environmental analysis has been prepared early during the planning process. The knowledge gained is useful during the further stages of project development.

The methods have further use during engineering design. In those instances where detailed environmental information has been prepared (land forms, soils, rocks, vegetation, drainage, land use, etc.) the maps showing distribution of environmental characteristics become the basis for planning field sample collection. Much can be done to locate and evaluate construction materials to locate haul roads and locate drilling activities in support of foundation design.

As a project moves into the construction phase, remote sensing can play an important part. For example, a pre-construction photographic record showing non-project related conditions (vegetation, land use, erosion, habitation, etc.) provides a very important record should litigation occur over some stressed condition. During construction, periodic photo coverage provides an important means of determining and evaluating construction progress and a basis for detecting unforeseen stressed conditions that may or may not be project related. Upon completion, photography should once again be obtained to provide a record of "as built" conditions.

Upon completion of construction and during project operation, periodic coverage (at least annually) should be obtained of the project area for purposes of detecting and evaluating any environmental sensitivities not previously noted or anticipated. This collection of periodic coverage - pre-, during and post-construction becomes a valuable record should litigation occur.

Hazards Assessment and Project Planning

General - The process used by the Corps in planning a construction project typically involves:

- collection and interpretation of historical photography which allows one to study the evolution of natural changes as well as man's.
- extraction of environmental data from photography and assembly of overlays for each environmental factor of concern.
- team selection of sites for field verification to gather ground truth.
- field work and intensive interdisciplinary discussion.
- production of a technical report.

Installation Planning - Many government facilities occupy large tracts of land having a wide variety of environmental conditions. By Executive Order No. 11752 usage of these lands must comply with environmental quality standards. Such compliance requires planning and the ability to rapidly collect large amounts of environmental data. At one installation, training disturbed surface vegetation to various degrees, creating dust and erosion problems. We used remote sensing to learn the status of the environment in the training areas so we could keep these problems from getting out of hand. The imagery collected and special analytical procedures were used to produce a map showing levels of vehicle usage. Maps provide information for planning future training exercises so as to prevent overuse of portions of the training areas. Information on vehicle usage has not been available previously because of the prohibitive time and manpower required to obtain these data by conventional procedures.

Geological and Soils Investigation - In order to plan the location of a large dam we have to consider both soil characteristics and the geological structure. Linear features, which require special attention, are conveniently analyzed using side looking airborne radar (SLAR) and aerial photographs prior to on site investigation. To date we have made greatest use of SLAR in the Upper Missouri Basin in the Northwest. Here we have used radar for soils investigation. Elsewhere we have also been using SLAR to analyze large areas for seismic hazards. This helps to locate structures better to reduce possible damage from earthquakes, and to determine which design criteria to use. For the Tennessee Tombigbee Waterway we used high-altitude aircraft photography for environmental studies and in our geological investigations to locate construction materials.

Flood Plain Analysis

We use a variety of imagery for our flood plain analyses. Again, SLAR is particularly useful because it works in cloudy weather which we often have when we are fighting floods in places like St. Louis. We can use remote sensing to plot inundation damage soon after it occurs and relate it to channel profiles and our hydrologic models.

Coastal Protection

We have found that multi-temporal imagery is especially useful in places like Cape Cod for assessing shoreline changes. We need to do this to plan corrective measures, beach fill, beach control structures, and entrance structures and for locating disposal areas for dredged materials. The multi-temporal coverage also allows us to record historical changes and provide input to our prediction models. Our Los Angeles District has used aerial photography to evaluate the wave climate in channel entrances. Elsewhere we have also used land-based imaging radar in a research mode to improve our data collection capability. Hopefully this leads into use of SEASAT radar.

In the area of international cooperation we have been using MSS data to locate hazards to navigation such as unknown islands, submerged reefs, and locating poorly known islands. We studied the Fiji Islands with MSS data from LANDSAT and formed a color composite. The red shows those islands that are far enough out of the water to support vegetation well. We gave this information to the Hydrographer of the Navy in England. The following is a statement extracted from a letter we received.

"Indications are that many coral atolls are out of relationship with neighboring atolls and islands. Largest discrepancy found to date is an atoll 2 miles out of its charted position."

Our Seattle District has used some of our newer techniques in a research mode supported by our Cold Regions Research and Engineer Laboratory in a study of Cook Inlet Alaska. Such studies will have increasing importance as public concern increases over navigation and safety of large super tankers.

Dam Safety

As part of the National Program to gather information on dams, the Corps has used LANDSAT imagery in the Missouri River area to pinpoint locations of water bodies above a certain size. Initially we used manual techniques but subsequently used digital techniques available at our Waterways Experiment Station or from NASA. The digital studies were never funded to continue. However, a resumption of the dam inventory work is now under consideration by Congress. The Corps is on record that LANDSAT will be used as an operational tool to update the inventory if the program is funded.

Operations and Maintenance

Keeping our completed waterways navigable and predicting runoff are continuing problems. These are areas where our models have not caught up to the data available. Therefore, our districts are working in an experimental mode with our labs and the Hydrologic Engineering Center (HEC).

Our Waterways Experiment Station is attempting to classify types of aquatic plants using remote sensing. If we can do this, then the district can better specify a treatment to control the plants.

We are also aware that infrared (IR) imagery can show heat loss. In the Corps we have applied this fact to locate leaky roofs in need of repair. Moisture getting into a roof changes the heat conductivity of the insulation. The change shows up in IR.

In the dredging area we are using machined processed LANDSAT data to locate suspended materials in a tributary that will be deposited eventually in a navigation channel.

In the area of runoff estimation we are using remote sensing to classify impermeable surfaces in land-use mapping. The data goes into a HEC runoff model.

The Corps and NASA are cooperating in an ASVT to develop automated input for hydrologic models using LANDSAT data. We have tested some small river basins in California using supervised classification and are now testing in the Oconee River Basin in Georgia. We will also investigate the feasibility of using unsupervised routines. However, the gross output from LANDSAT is still more than we can use in our hydrologic models.

For land-use mapping there is still overall preference for aircraft photography in developed areas. The NASA RB-57 imagery has allowed us to map in better detail than Skylab imagery which is still preferred over LANDSAT data.

Regulatory Operations

The Corps of Engineers maintains navigable waterways which are defined as:

"Navigable waters of the United States are those waters which are presently, or have been in the past, or may be in the future susceptible for uses for purposes of interstate or foreign commerce."

This function requires the issuance of permits according to the following policy.

"The decision whether to issue a permit will be based on an evaluation of the probable impact of the proposed activity on the public interest . . . No permit will be granted unless its issuance is found to be in the public interest."

Generally it can be said that we must presently employ a variety of labor intensive activities to regulate the use of navigable waterways and to enforce the permit program. We are experimenting with remote sensing techniques, but the entire regulatory area appears to be a fertile field for investigation. We need labor-saving remote sensing techniques that will hold up in court! Our present methods are manual. We are going into aircraft surveillance using state-of-the-art methods. We eventually hope to improve our change detection techniques through digital processing.

NEEDS FOR FURTHER DEVELOPMENT

There are three major areas requiring continued investigation and intensive research and development to meet Corps' needs for remote sensing of the environment.

Sensor Technology - Our efforts to automate some analyses have been limited because existing LANDSAT technology is not yet operational, nor is it designed to meet Corps' needs. The resolution must be improved considerably and more timely coverage must be achieved. Meanwhile at ETL we are investigating all alternatives available to improve the Corps' use of advanced remote sensing technology.

Data Processing - The use of more advanced technology for remote sensing of the environment requires the development of increased automation using interactive analysis. An experimental digital interactive analysis laboratory now is operational at ETL. It will be improved, as needed, to handle the higher data rates associated with near-real-time systems needed for monitoring or with higher resolution systems needed for identification. The interactive system gives the human interpreter a computer assist that significantly enhances his ability to analyze an image.

For many types of analysis a digital system may not be needed. A more appropriate technology for many applications is a simple optical transfer scope which allows the user to superimpose remote sensing imagery on a base map. One can perform a type of change detection using such a system, update environmental baseline maps, and locate possible permit violations. ETL is currently developing this type of system to allow use of TV images during emergency and disaster recovery operations, but much remains to be done.

Models - To date exploitation of remote sensing imagery is inhibited by the inability of our models to fully use the data which can be provided by present systems. We need better hydrologic models to exploit present LANDSAT data. We are looking for new concepts also and have begun to look at a new mathematics technology, array algebra, to determine how it might affect the digital architecture of interactive systems.

CONCLUSION

This overview summarizes some of the more important observations made within the Corps of Engineers over a period of many years. Remote sensing of the environment is going to have to play an increasingly important role and new techniques must be found to provide more timely and accurate analyses that are affordable. Technologists are encouraged to work more closely with the operating districts of the Corps and direct developmental efforts towards satisfying existing needs. Meanwhile, the Corps is making a deliberate effort to see what new technology we can pull in and to do a better job articulating our needs in terms that technologists can understand.

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ATMOSPHERIC SOUNDING WITH PASSIVE

MICROWAVES: REVIEW AND PROGNOSIS

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ABSTRACT

Global maps of temperature profiles 0-20 km and of total water vapor and liquid water over ocean have been obtained from satellite-borne microwave spectrometers. Future satellites should extend the altitude range above 100 km and permit monitoring of H₂O, O₃, CO, N₂O, and other trace constituents. Operational microwave temperature-sounding spectrometers are scheduled for launch on both military and civilian U.S. satellites, and future improvements can be expected.

1. INTRODUCTION

Passive microwave sensing techniques are employed in geophysics, radio-astronomy, biomedical and other areas. The special value of these techniques results primarily from the facts that 1) microwave receivers can sense thermal radiation with 1-second sensitivities as high as 10^{-2} °K, 2) microwave radiation penetrates most matter much more readily than does infrared radiation, which is the usual alternative technology, and 3) many gases have microwave resonances which can readily be resolved, and which permit observation even in some cases where other spectral regions are inadequate. Geophysical applications have been reviewed by Staelin (ref. 1), Tomiyasu (ref. 2), Waters (ref. 3), and others.

The dominant microwave absorbers in the atmosphere are H₂O, O₂, clouds, and precipitation. Figure 1, prepared by P. W. Rosenkranz, illustrates the typical opacity of the terrestrial atmosphere due to water vapor, oxygen, and clouds. Many typical trace constituents also have weak but quite observable spectra. The microwave spectral properties of the atmosphere have been reviewed by Staelin (ref. 1), Waters (ref. 3), Rosenkranz (ref. 4), Liebe (ref. 5), and others. With the recently available sensitive receivers in the 100-300 GHz region, many additional microwave spectral lines are being detected in the atmosphere for the first time, such as those of O₃ and CO near 100-200 GHz.

2. SOUNDING OF ATMOSPHERIC TEMPERATURE PROFILES

Two basic geometries are appropriate for satellite sensing of atmospheric temperature profiles; the "nadir mode" wherein the satellite sensor views the atmosphere at any desired angle such that the ray intercepts the terrestrial surface, and the "limb-scanning mode" for which the ray does not intercept the earth but passes through the atmosphere at the limb of the planet; only nadir-mode microwave systems have been built to date.

At present only two satellites carry passive microwave sounders for temperature profile measurement; Nimbus-5 carries NEMS, launched December 12, 1972 (ref. 6) and Nimbus-6 carries SCAMS, launched June 11, 1975 (ref. 7).

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They each have two channels near 1-cm wavelength for observing the surface and atmospheric water, and three channels near 0.6-cm wavelength which are on the opaque wings of the 0.5-cm oxygen absorption complex; they measure thermal radiation originating from different atmospheric levels 0-18 km. Improved 4-channel and 7-channel spectrometers are to be part of the operational weather satellite system beginning in 1978.

An important property of microwave temperature sounders is their ability to penetrate all cirrus clouds and almost all non-precipitating clouds. A study of the degradation of NEMS temperature retrievals by clouds (ref. 8) shows that only intense precipitation bands, such as the ITCZ or major extratropical storms, have any measurable effect on temperature retrievals. This effect arises from perturbations in the brightness temperature of ~ -5 to $+2$ °K for channels sensing $\sim 3-8$ km altitude. These effects are normally negligible because most heavy clouds have temperatures close to those of the observed brightness temperatures, and because most heavy clouds do not fill the entire ~ 300 -km viewing zone of NEMS. Approximately 0.4% of NEMS observations with that channel which sensed temperatures near 4-km altitude were perturbed more than 1 °K, and these were primarily over the inter-tropical convergence zone (ITCZ) (ref. 8).

Analyses of the accuracy of such temperature retrievals for NEMS were performed by Waters *et al.* (ref. 9) and Wilcox and Sanders (ref. 10). Receiver noise for NEMS was ~ 0.15 °K per sounding. Calibration errors are believed to be less than 2 °K and essentially constant; therefore they contribute primarily to mean retrieval errors of $\sim \pm 2$ °K, but very little to rms errors about the mean, which range from $\sim 1^\circ$ to $\sim 4^\circ$. The majority of the inferred retrieval errors are believed to result from coarse weighting functions and radiosonde errors.

The 60-GHz band of oxygen is not the only opaque region that can be used for temperature sounding; the isolated 118.75 GHz resonance of O_2 is even more opaque than the 60-GHz complex. Although cloud effects can be perhaps twice as great near 118 GHz, the effects are still important primarily in the ITCZ and large extratropical storms. The weighting functions are slightly broader at 118 GHz than near 60 GHz, and can reach to altitudes near 80 km at the very center of the resonance.

Limb-scanning observations (ref. 11) of the atmospheric temperature profile require large antennas in order to resolve the limb of the planet, which may be ~ 1000 km from the satellite. The excellent altitude resolution for limb-scanning systems arises because the majority of the emission originates within ~ 2 km of the ray tangent height if the atmosphere is not opaque. If the satellite is 1000 km from the tangent point for a given ray, then an antenna beamwidth of ~ 7 arc minutes is required to achieve 2-km vertical resolution. This requires an antenna ~ 3 m long in the vertical direction at 60 GHz, or ~ 1.5 m at 118 GHz. These dimensions are within the capability of the space shuttle and modern antennas.

3. SOUNDING OF ATMOSPHERIC COMPOSITION

Figure 1 illustrated resonances of oxygen and water vapor. Other important molecules include O_3 , N_2O , and CO . The spectra of these and other molecules was recently reviewed by Waters (ref. 3).

Such spectral lines can be observed passively against three different backgrounds: 1) cold space reflected by the ocean, 2) an opaque atmosphere at a different temperature that provides contrast, and 3) cold space, as in the limb-scanning mode. Passive microwave satellite measurements of atmospheric composition have been made only of water vapor and liquid water over ocean; the high reflectivity of ocean (~ 60 percent) near the 1.35-cm resonance provides a cold background for thermal emission from both water vapor and liquid water (ref. 12).

Atmospheric water vapor near 22 GHz appears in emission against the cold ocean background with a line shape and amplitude that is nearly proportional to the absorption coefficient of the atmosphere. The H_2O line width for each

atmospheric layer is proportional to its pressure, and thus the total line shape contains information about the water vapor profile which can be retrieved. Linear and quasilinear techniques have been used successfully for estimating water vapor abundances and profiles; the problem is sufficiently linear that they generally suffice (refs. 13, 14, 12).

The presence of clouds and precipitation complicates water vapor retrievals only slightly because the non-resonant character of cloud absorption can be distinguished from the resonant character of water vapor (see Fig. 1), as noted by Staelin (ref. 13) and others (refs. 14, 12). Rosenkranz *et al.* (ref. 14) concluded theoretically that rms accuracies of 1.3 mm precipitable water vapor and 0.06 mm liquid water could be obtained from observations over ocean at only two frequencies, such as 22.2 and 31.4 GHz. Examples of water vapor and liquid water retrievals are shown in Fig. 2; these are two-week averages of total water (g cm^{-2}). Lighter areas in the figure are wetter. Ocean roughness emulates liquid water below 45°S latitude.

The most sensitive and precise way to measure atmospheric composition is by means of limb scanning. The path length of the radiation is ~ 300 km near the tangent point (where the ray is parallel to the terrestrial surface or geoid), as contrasted with ~ 10 km for nadir observations. This factor of ~ 30 for path length is augmented another factor of ~ 10 by the greater contrast provided by cold space, as opposed to that supplied by the underlying atmosphere for nadir observations. Waters (ref. 3) has analyzed this possibility for several trace constituents and it appears that CO might be sensed up to ~ 100 km or more using the 230 GHz resonance, H_2O to ~ 100 km using 183 GHz, O_3 to ~ 100 km at 184 GHz, etc.

4. SOUNDING OF ATMOSPHERIC PRESSURE

There are at least two approaches to the sounding of atmospheric pressure using microwave techniques and a single satellite. These include measurement of 1) the pressure-dependent differential atmospheric absorption near a strong resonance of a constituent like O_2 , which has a nearly constant mixing ratio; this can be done in principle using radar techniques from a satellite viewing nadir over ocean, and 2) brightness temperatures at the limb at one or more frequencies, as a function of the altitude of the ray tangent point, which must be known *a priori* with precision greater than that desired for the measurements of pressure altitude. The successful operation of any of these techniques would require a level of precision in one or more particulars beyond the present state-of-the-art; several of these necessary advances appear feasible.

5. ACKNOWLEDGMENT

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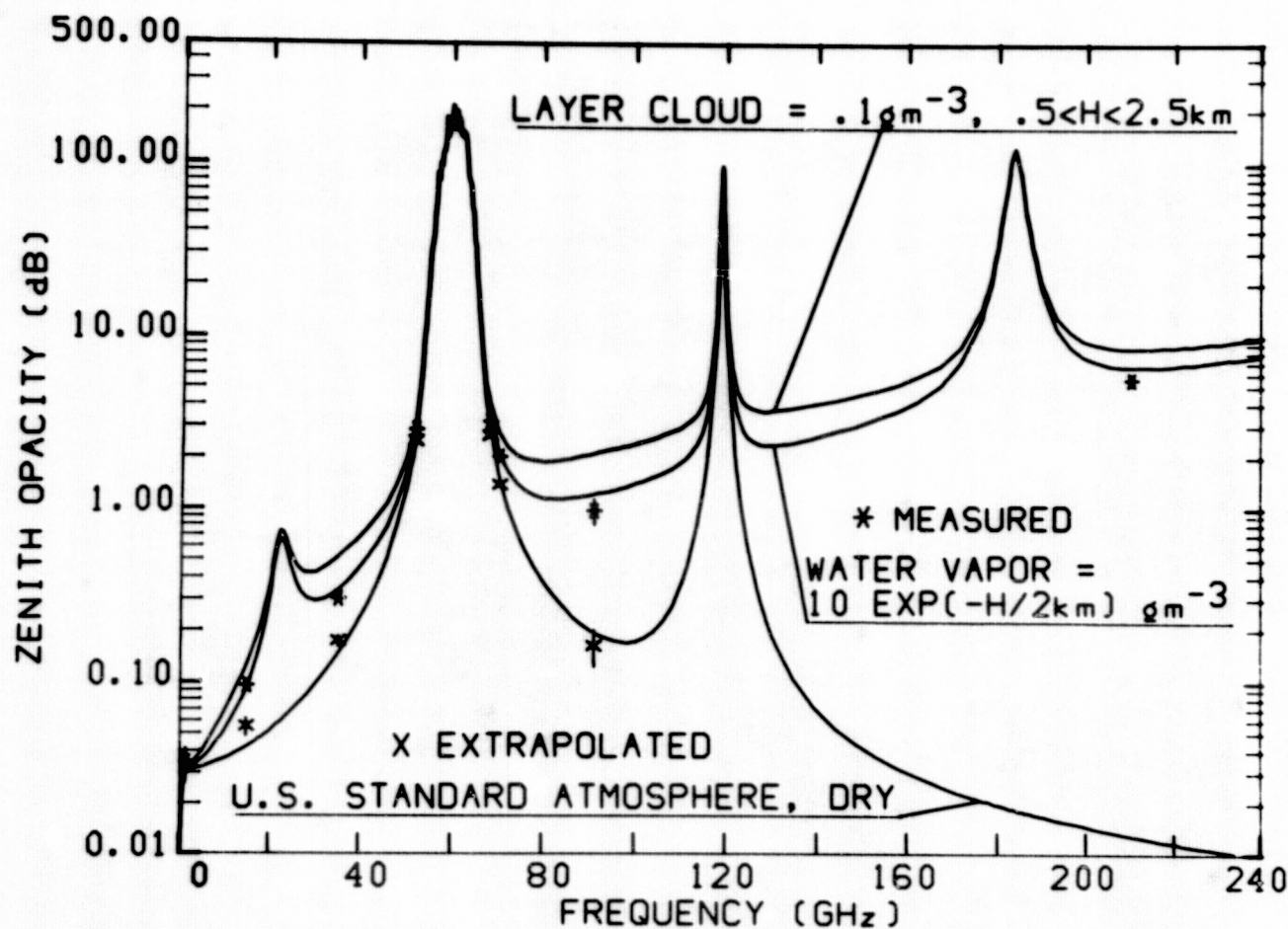


FIGURE 1. Sea level zenith opacity for oxygen in the U.S. Standard Atmosphere and for 2 precipitable cm water vapor distributed exponentially with 2 km scale height. The effects of a 2-km thick stratus cloud are also shown. Typical measurements for O_2 alone and O_2 plus H_2O are indicated by stars.

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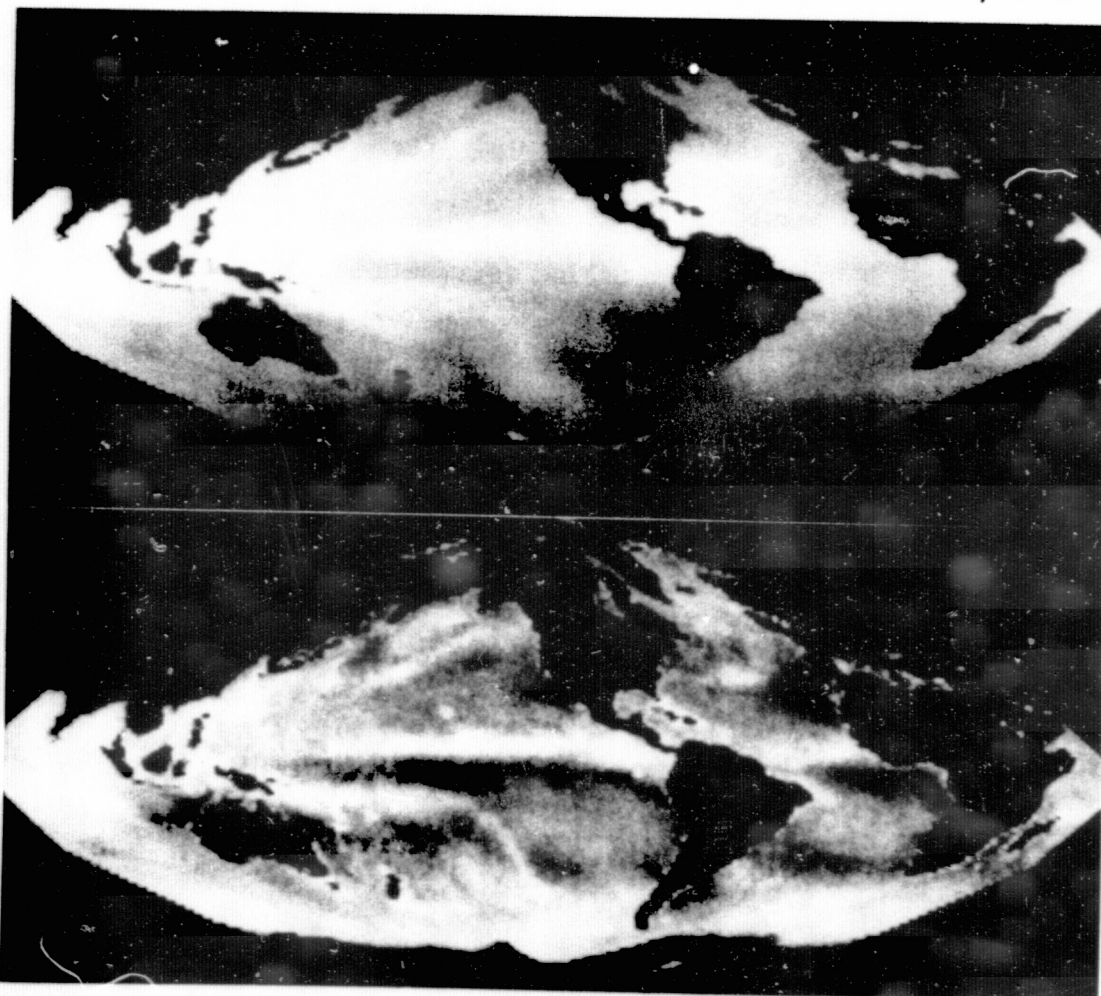


FIGURE 2. Two-week average of retrieved water vapor and liquid water densities over ocean (g cm^{-2}). Data provided from the Nimbus-6 scanning microwave spectrometer, i.e., brightness temperatures at 22.2 and 31.6 GHz.

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SPACE RADAR SYSTEM SPECIFICATIONS

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ABSTRACT

Satellite remote sensing activities in the 1980's and beyond will undoubtedly utilize a multitude of sensors including optical, thermal infrared and active (radar) and passive microwave instruments. Among these sensors, the latest newcomer onto the satellite platform scene is radar. Skylab provided the first opportunity to test a radar system in the non-imaging scatterometer mode from space in 1973, and SEASAT-A, scheduled for a 1978 launch, will carry the first synthetic aperture imaging radar aboard a space platform for civilian purposes. The SEASAT-A system, now in the construction stage, was designed primarily for oceanographic studies. However, plans also call for the development of a spaceborne imaging radar for land applications. Specifications for this system, however, are not yet finalized. The purpose of this paper is to propose system specifications for an imaging radar whose primary objective is to provide useful information for land applications including hydrology, agriculture and geology.

1. INTRODUCTION

Unlike the camera, the invention of which is credited to Niepce in 1822, radar is a relatively new addition to remote sensing's battery of instruments. While a U.S. Patent [1] was issued as early as 1934 for a "System for Detecting Objects by Radio", it was not until World War II that long range RADAR was coined. Since World War II, rapidly advancing technology has allowed radar to become increasingly exploited by the civilian and military sectors of society to the point that radar and our dependencies upon radar are often taken for granted.

In 1978 the exploitation of radar will increase still further with the launching of SEASAT-A. As its name implies, SEASAT-A is a satellite whose goal is to test the applicability of remote sensing devices for providing global surveillance of the oceans and their associated phenomena. As part of its repertory of remote sensors, a synthetic aperture imaging radar will be used to monitor the ocean wave dynamics. This radar will be the first civilian imaging radar to be placed in earth orbit.

Proposed for the early 1980's is a second spaceborne imaging radar. Unlike the system carried onboard SEASAT-A, however, this system would be an experimental land applications imager and would be carried aboard the space shuttle orbiter rather than being borne on a free-flying satellite. Because the mission duration of the shuttle orbiter will only be on the order of seven days, the utility of a shuttle radar would be somewhat limited. In spite of this drawback, however, hopes are high for the implementation of the proposed radar system so that the capabilities of a land applications, spaceborne radar can be demonstrated.

As presently envisioned, a future orbital radar would operate along side other sensors, in some cases providing unique information such as high resolution soil moisture maps. In other cases it would serve to complement different sensors. For example, when cloud cover is present radar provides a unique means to acquire data from a spaceborne platform. However, when atmospheric conditions allow the operation of optical sensors, radar imagery can complement the optical imagery. An example of how radar imagery can serve to complement optical imagery is

shown in Figure 1. In this figure, a LANDSAT MSS color composite image and a radar image of the San Diego area are shown along with the optically combined LANDSAT/radar image. Even a cursory comparison of the two images indicates the advantage of the MSS/radar combination technique. However, as of yet the specifications for the proposed space shuttle imaging radar (SIR) are not definitive and are the subject of much discussion. Such discussion stems from the fact that because of the dependencies of σ^0 (the radar scattering coefficient) on frequency, polarization and angle of incidence, the specification of these three parameters will have a significant impact on the utility of the data for each particular application.

In no sense should radar be considered a "cure-all" for solving every problem being investigated by the remote sensing community. Rather, as with any sensor, it should be considered a remote sensing tool more suitable for some applications than for others. This paper proposes system specifications for a shuttle-like radar aimed at portions of the geologic, water resources and agriculture and soil applications areas. Specifically it is felt that such a system would be of particular value to the application areas of general geology, snow field monitoring, crop identification and soil moisture determination.

2. RADAR CAPABILITIES AND ADVANTAGES

Because of the successes of the LANDSAT program it might be questioned as to whether a radar equipped, earth resources satellite is actually needed. When considering such a question it must be realized that optical sensors, such as LANDSAT'S MSS, and active microwave sensors, such as the proposed shuttle radar, are distinctly different types of sensors, each acquiring vastly different types of information. Thus, when used in tandem, optical sensors and radar can provide data having an information content highly superior to data provided by either sensor alone. Moreover, for some applications, radar is an undeniably superior sensor.

Perhaps radar's most unique and appealing advantage over optical sensors is its ability to acquire timely data without regard to solar illumination or the presence of cloud cover. This is particularly true when a user application requires repetitive image acquisition on a routine basis. One such application requiring dependable, multirate image acquisition is that of crop identification. Because it is extremely doubtful that reliable and accurate crop inventories are possible using single date imagery acquired by either optical or microwave sensors, it is necessary to use multirate imagery for increased crop identification accuracy. This technique has been the focus of the investigations of many researchers. Steiner [2], for example, investigated the use of the temporal dimension for purposes of improving crop identification accuracy and stated that on the basis of his work, "accurate crop surveys could be conducted using remote sensing techniques within the visible spectral band, provided that observations were repeated a fair number of times during the growing season. We are aware of the difficulties produced by the presence of frequent cloud cover over certain areas, of course. However, data gathering at more irregular intervals might produce satisfactory results, or else the use of another spectral band less or not affected by clouds might be the solution." Radar, with its ability to "see" through cloud cover, is certainly a viable candidate for such an application.

Perhaps one of the better demonstrations of the efficacy of radar is presented in Figure 2 which depicts the areas imaged by the GEMS* radar system to date. Operated by the Goodyear Aerospace Corporation, the GEMS system is one of only two (the other being Motorola) commercially operated imaging radars in the United States. To date more than 12 million square kilometers have been imaged with GEMS in 11 countries on four continents. Note that many of the areas shown in Figure 2 are those having rather high levels of mean annual cloud cover. This is particularly true for the Amazon River Basin in South America where all countries sharing the basin have obtained GEMS coverage. It should be pointed out that Figure 2 depicts only those areas imaged with the GEMS system. Figure 1a is a sample of GEMS imagery acquired over San Diego.

Because of their dependence on solar illumination, optical sensors such as LANDSAT MSS generally require placement of the satellite in a sun synchronous orbit. The orbit of a spaceborne radar, on the other hand, can be chosen with more freedom. In particular, the orbital altitude can be varied over larger ranges allowing a greater choice of orbital period which in turn dictates the target revisit period. Moreover the time of day at which a target is viewed is no longer an overriding consideration. This is certainly not true of optical sensors which can only operate during daylight hours. Even during daylight hours, care must be taken in analyzing optical data to account for variance introduced by solar angle effects.

*Goodyear Electronic Mapping System

Radar also has the unique capability of making cross-polarized measurements. This means transmitting and receiving the radar signal with antennas having orthogonal preferred polarization characteristics which is a direct result of the ability to control the target illumination. By their very nature, passive sensors are not capable of such measurements. Moreover, because of the vast difference in signal wavelengths employed by optical and microwave sensors, each responds to target structure in a different manner. In the optical window, for example, most targets appear very rough, often scattering energy in somewhat of an isotropic manner, minimizing most structural characteristics of the terrain. In contrast, changing the radar signal wavelength results in an effective change in target roughness which allows, in some cases, inferences of target structure to be made. While it may be argued that the isotropic scattering behavior of targets viewed by optical sensors may be desirable (e.g. dependence on viewing angle is minimized) the control of effective target roughness by radar offers many opportunities for target study.

Microwave sensors are also rather unique in that they are particularly sensitive to moisture content of natural targets such as soil, crops and snow. This is a result of the fact that at common radar frequencies the dielectric constant of water is much higher than the dielectric constants of most dry natural targets. In Figure 3a and 3b the dielectric constants of soil and snow are plotted versus soil moisture and snow liquid water content. Note that the dielectric constant of clay, for example, increases from about 3 to 22 as moisture changes from 0 g/cm³ to 0.40 g/cm³ (Figure 3a).

While a multitude of applications for an earth oriented radar have been identified, they can generally be subclassified into two groups. In this paper they will be identified as either parametric applications or contextual applications. This division is a function of how information is extracted from the imagery. A contextual application, as the term contextual implies, relies on image context and spatial variability for proper interpretation. A geological application, for example, is contextual since the interpreter relies primarily upon spatial feature orientation for information extraction. This is in contrast to a parametric application in which information is extracted by a study of image tone. More precisely it is the magnitude of σ^0 , the radar scattering coefficient, which is the primary source of information for a parametric application.

The successful exploitation of a sensor system for a parametric application is generally predicated on the quality and quantity of information available on the physical processes which govern the characteristics of the radiation to be detected. The development of functional expressions relating microwave backscatter response, σ^0 , to terrain parameters of interest is thus fundamental to the full exploitation of radar's capabilities. The problem of developing such relationships can be approached from a theoretical, empirical or semi-empirical direction. If it were possible to completely describe both the electrical and geometrical characteristics of terrain, then it would be theoretically possible to develop a completely accurate scattering model. The development of such a model would certainly be welcomed although it is probably safe to assume that the development of such a theory is virtually impossible. In some situations it is possible to approximate the terrain by either a probabilistic or perhaps a deterministic function such that the solution of the scattering problem is more practical. In general, however, such models are more useful in developing a fundamental understanding of the scattering process rather than for use in operational remote sensing systems.

The next most favorable alternative is to perform scattering experiments with the goal of developing a reasonably accurate and complete scattering coefficient data base for each terrain feature or cover of interest. With such a data base attempts can then be made to develop semi-empirical models which relate radar measurements to ground truth observations. In general these empirical models are mathematically simpler than the models based entirely on theory and, when used in conjunction with theoretical considerations, they can add valuable insight into the dependence of the terrain scattering coefficient on the wave parameters (wavelength, angle of incidence and polarization). Since these relations are generally a function of the signal parameters, it is desirable to make measurements over as wide a range of signal parameters as possible.

3. PARAMETRIC APPLICATIONS

In 1972 the first of a series of radar spectrometer scatterometers was constructed and employed in a program designed to gain a better understanding of the scattering properties of various crop species and soil surfaces. Termed the MAS 4-8 (Microwave Active Spectrometer, 4-8 GHz), the system was a truck-mounted FM-CW radar system capable of making measurements of

σ° at frequencies between 4 and 8 GHz, at angles of incidence between 0° (nadir) and 70° for HH, HV and VV polarizations. The success of the system operation spurred construction of an additional, higher frequency system and extension of the MAS 4-8 to lower frequencies. Presently, the combination of the two systems can provide coverage over the 1-18 GHz range plus a 35 GHz channel. Since 1972, in excess of 3.5 million individual measurements of σ° have been acquired using these systems. Table I presents nominal specifications for both radar spectrometers while Figure 4 presents a photograph of the MAS 1-8 system in operation.

Because the MAS systems are not imaging radars, they are of limited use for applications which rely heavily on image context for information extraction. The systems are suited, however, for parametric applications where the magnitude of σ° is the prime source of information rather than reliance on spatial information, such as texture and shadow. Among these applications are: a) monitoring soil moisture content, b) monitoring snowpack wetness, and c) crop species identification. These three application areas have been investigated using the MAS systems and, in light of specifying system parameters for a spaceborne radar, are discussed in the following sections.

3.1 MONITORING SOIL MOISTURE WITH RADAR

Extensive experimental work has been conducted to evaluate the utility of radar as a soil moisture sensor. A summary of the status of radar soil moisture sensing is reported elsewhere in the Proceedings of this symposium [3]; hence to avoid repetition, only the significant conclusions are included herein. Based on an evaluation of the active microwave response to soil moisture content, surface roughness, and vegetation cover, it was concluded that radar can provide quantitative soil moisture information for both bare and vegetation-covered soil provided its system parameters are properly chosen. The recommended parameters were: a) microwave frequency in the 4-5 GHz range, b) 7° - 17° angle of incidence (relative to nadir) range, and c) HH or VV polarization with the addition of cross polarization as highly desirable. It was also pointed out that the radar performance as a soil moisture mapper can be significantly enhanced if auxiliary information on vegetation cover is provided by an independent sensor such as MSS scanners (under clear sky conditions) or an imaging radar operating in the 8-18 GHz band at angles of incidence higher than 40° (as discussed in section 3.3).

3.2 MONITORING SNOWPACK WETNESS WITH RADAR

In some areas of the world, the major source of water for power, irrigation, and human consumption is from snowpack melt. Accurate measurement of the runoff is therefore very important for both flood control and proper conservation of this resource. Snowpack water equivalent is the total water content of the snowpack per unit area. The traditional method used to acquire data on water equivalent involves the direct sampling of snow depth and density. The measurements are then related to runoff by one of several methods: historical normal, index method, water balance method, or hydrologic methods. These methods have the disadvantage of using a limited number of discrete samples to estimate water equivalent on a large area basis, which is both laborious and not very accurate. Remote sensing has the potential to provide more accurate large-scale snowpack information, which can serve to improve the hydrologist's prediction of runoff.

Since 1975, two experiments have been conducted by the University of Kansas Remote Sensing Laboratory to evaluate the response of microwave sensors to snow cover. The first experiment, conducted in Lawrence, Kansas in 1975 employed the MAS 1-8 system. The results of this investigation indicated that the radar scattering coefficient was highly dependent on snow condition variations and provided the stimulus to conduct a second, more extensive snowpack experiment. This second investigation conducted in early 1977 in Steamboat Springs, Colorado resulted in the acquisition of scattering data from a broad range of snow conditions. Moreover, active microwave data were acquired over the 1 GHz to 18 GHz range and at 35 GHz and passive data were acquired at 9, 37 and 94 GHz.

Figure 5 presents a sample of the 1975 experiment data. These data were acquired at 6.25 GHz at 70° with an HH antenna configuration. While only 11 data points were acquired, the correlation coefficient, ρ , was -0.797, statistically significant at the 0.99 level of significance. In Figure 6a, curves are presented depicting the correlation coefficient between σ° and m_e for other angles and frequencies. Although ρ is rather high at nadir at frequencies higher than about 5 GHz, image resolution restrictions at nadir removes a nadir viewing system from consideration. While the values of ρ at the higher angles are not remarkably large, the magnitude of ρ indicates an increasing trend with angle and frequency. Similarly this is true for the sensitivity of σ° to m_e as shown in Figure 6b.

It is unfortunate that provisions were not available in 1975 to measure the snow liquid water content as it is very likely that it is this parameter which drives the snow scatter phenomenon. During the 1977 experiment, however, liquid water content was measured and a preliminary examination of the data indicates that σ^0 is highly dependent on this variable. Moreover, the trend for the sensitivity of σ^0 to m_t to increase with frequency appears to be borne out by the 1977 data.

3.3 CROPLAND INVENTORIES WITH RADAR

Of utmost importance in any cropland management program is the ability to quickly and accurately identify those crop types of interest under cultivation within a given region. For instance, yield predictions cannot be made without a knowledge of the acreage occupied by a given crop nor can growth stage be determined until the crop species have been identified. Presently, orbital sensors are being investigated as possible aids for the cropland manager. Those sensors receiving the majority of attention are of two general types, the passive optical sensors and the active microwave sensors. While both optical and microwave sensors are capable of making multispectral and multipolarized measurements, the microwave sensors provide a dependable added measurement dimension, the temporal dimension. While the optical sensors can provide temporal data under ideal atmospheric conditions, microwave sensors, particularly the active microwave sensors, can provide temporal data regardless of cloud cover and time of day. It is this distinguishing characteristic which makes the active microwave sensor so appealing.

An ongoing investigation of the radar response of croplands has led to the following design recommendations for an active microwave orbital sensor for crop identification applications. a) To adequately (correct classification of at least 90% of all resolution cells) discriminate among and classify crops the temporal dimension should be employed. It presently appears that repetitive coverage of a ten day period will be needed. b) Current indications are that a vertically polarized signal having a frequency of about 14 GHz is most suitable for crop identification. In lieu of this choice a dual polarized signal of 9.0 GHz may probably be used. c) Assuming a signal choice of 14 GHz VV has been made and further assuming that the temporal dimension is employed, the addition of either an added frequency or an added polarization will provide nearly identical additional information (over a 14 GHz, VV temporal channel) for classification purposes.

Earlier studies of radar response to vegetation [4] have indicated that to avoid the influence of soil moisture on σ^0 , the radar scattering coefficient, frequencies higher than about 8.0 GHz and angles of incidence (measured from nadir) greater than about 40° must be employed. Bearing this in mind a temporal data base was constructed using data gathered at an angle of incidence of 50° at six different frequencies in the 8-18 GHz frequency interval. Both HH and VV data have been employed. For example, Figure 7 presents the temporal variations of σ_V^0 (dB) as measured at 14.2 GHz. Note that five crop types were studied. Since different crops were cultivated during the period extending from May 19 to June 28 (see Figure 7) than during the remainder of the season it is, in general, necessary to break the total season into two parts if the temporal dimension is to be effectively employed.

While the data such as those depicted in Figure 7 were gathered under rather controlled conditions, actual data collected by an orbital sensor will undoubtedly include various errors and uncertainties. The sources of these errors and uncertainties are numerous but they can be grouped into three major classes: a) those introduced by signal scintillation, b) those introduced by natural variations in the scattering properties of targets within a supposedly "homogeneous region" and c) those introduced by sensor instabilities. For this study these three effects were modeled in accordance with the preliminary design specifications for the shuttle imager as estimated by the Hughes Corporation [5].

The first task of the investigation was that of rank ordering the 12 measurement dimensions in terms of their discriminating power. This ordering was done on a day by day basis using data sampled from the temporal dimension approximately every five days. This produced 24 temporal measurements from the 120 day data base. The data were ordered using a stepwise technique based on an F-ratio of between class variance to within class variance. Of the 12 available measurement variables, $\sigma_{14.2V}^0$ (σ^0 as measured at 14.2 GHz with a VV antenna configuration) was selected on 19 of the 24 sample days as having the greatest discriminating power and was thus chosen as being the best of the 12 (6 frequencies x 2 polarizations) available variables.

Having removed the variance accounted for by $\sigma_{14.2V}^0$, the remaining 11 variables were rank ordered. This second step of the analysis indicated that either $\sigma_{9.0H}^0$ or $\sigma_{17.0V}^0$ was

acceptable in terms of their discriminating power. However, because of the technical and economic difficulties involved in producing a 17.0 GHz system [5] $\sigma^{\circ}_{9.0H}$ was chosen as the second discriminating variable. Moreover, the 9 GHz variable is of particular interest since 9 GHz is the frequency presently under consideration for the proposed shuttle radar.

Some results of using these variables ($\sigma^{\circ}_{9.0H}$ and $\sigma^{\circ}_{14.2V}$) in a linear Bayesian classifier are presented in Figure 8. Note that the temporal dimension has not yet been employed. Using only a single measurement dimension, $\sigma^{\circ}_{14.2V}$, the best classification occurs on day number 25 at which time 89% of the resolution cells (3200 in all) were correctly classified. Using both $\sigma^{\circ}_{14.2V}$ and $\sigma^{\circ}_{9.0H}$ increases the percentage of correct classification to 95%. While 95% is an adequate rate of correct classification, this rate occurs during the early part of the summer when only wheat, corn, alfalfa and bare soil were present. This does not allow for the subsequent classification of milo and soybeans after they have emerged. Moreover, during the subsequent portion of the summer the percentage of correct classification is relatively poor.

Figures 9, 10 and 11 present results using the temporal dimension for a ten day revisit period. In these figures various combinations of the 9 GHz and 14.2 GHz variables are compared. For instance, in Figure 9, classification results using the 14.2 GHz, VV variable and the 9.0 GHz, VV variable are compared. Note that indeed the 14.2 GHz, VV variable is superior with about 95% and 83% accuracy being attained 30 days subsequent to the initial sampling day of both temporal segments. The 9.0 GHz, VV accuracies are only 90% and 66% after 30 days for the first and second segments, respectively.

Figure 10 compares 14.2 GHz, VV results with 9.0 GHz, HH and VV results. Note a choice of either variable set results in accuracies that are not significantly different after 30 days. Finally, Figure 11 presents a comparison of results using the 14.2 GHz, HH and VV, 9.0 GHz, HH and VV and 14.2 GHz, VV and 9.0 GHz, HH variable sets. Clearly the dual polarized 9.0 GHz variable set is inferior to either of the other variable sets.

Table II presents these, and other, results in somewhat of a different form. Presented in this table are the number of days necessary to reach a 90% rate of correct classification as a function of sensor parameters and revisit period, τ . Note that whereas dual polarized, 9.0 GHz data produced accuracies greater than 90% (after 30 days of observation) for $\tau = 5$ days, dual polarized 14.2 GHz data result in accuracies greater than 90% for $\tau = 10$ days. Moreover, if τ is fixed at five days, accuracies greater than 90% (after 30 days of observation) can be reached with dual polarized 9.0 GHz data or singly polarized 14.2 GHz data. It should be noted that if the criteria of acceptable accuracies (i.e. that the accuracy must be 90% or more after 30 days of sampling) is relaxed to 90% accuracies after 40 days of sampling, then the 9.0 GHz, HH and VV variable set is acceptable. Moreover, these accuracies can be further increased by making use of ancillary data such as previous years planting practices and prior classification results.

4. CONTEXTUAL APPLICATIONS

The fact that contextual applications of radar rely more heavily on the acquisition of imagery rather than numerical values of σ° has retarded the evaluation of radar's spectral dimension. This is a result of the sophisticated nature of an imaging radar which makes the construction of an imaging radar spectrometer a formidable task. For some contextual applications, however, this lack of spectral information is not an extreme hinderance such as in the detection of bodies of water. While the development of an imaging radar spectrometer would be a boon to the field of remote sensing, such development is not planned in the foreseeable future.

It is beyond the scope of this paper to discuss all the possible contextual applications of radar. Rather, only a few contextual applications will be discussed as examples of the utility of radar for applications in which context plays the prominent role in the information extraction process.

To the geologist, radar can offer some rather important features. Most important is the fact that the radar shadows produced by the terrain relief tend to enhance subtle terrain features which often go unnoticed on aerial photography. This effect is clearly demonstrated in Figure 12, a radar image acquired with the Motorola system near Birmingham, Alabama. Because of the shadow produced by the terrain relief, the folds in this area have been clearly enhanced. While the effects of shadow are desirable for the geologist using radar imagery, it is not possible to specify an optimum depression angle suitable for all areas of the world. Different depression angles should be chosen depending on the degree of relief in the area being

imaged. In 1971 a world map was published [6] specifying suitable ranges of depression angle for the various regions of the world. A portion of this map is presented in Figure 13. Note that excepting areas of extreme relief, the suggested depression angles fall in the 20° to 45° region (45°-70° relative to nadir).

The use of cross-polarized radar imagery has been found to be particularly useful in geologic investigations. In areas having little vegetation cover, for example, it was found that the cross-polarized return can be of aid in studying the surface configuration of rock formations [7]. Thus, while it is not possible to suggest an optimum frequency for geologic mapping, it is possible to suggest that depression angles in the 20° to 45° range represent a suitable compromise for most geologic applications. Moreover it is desirable for geologic purposes that cross-polarized imagery be acquired in addition to the like-polarized imagery.

As demonstrated during project RADAM, radar can be an invaluable tool for producing not only current land use maps, but also maps depicting potential land use for future applications. Using such maps, areas can be selected for agricultural development, transportation network construction, mineral exploration, urban expansion as well as a host of other developmental applications.

Radar also has applications in regulating man's use of the environment. A spaceborne radar could provide an effective means of monitoring and tracking oil spills, monitoring areas clear cut by the lumber industry and regulating the mining industry to ensure that areas which have been strip mined are properly reclaimed.

Cartographers would certainly benefit from imagery obtained by a spaceborne radar system not only in areas heretofore unmapped because of persistent cloud cover but also in many areas where map updating is necessary [8]. This is particularly true for the development of topographic maps where the relief enhancement provided by radar can provide unusually good presentations of terrain relief not apparent in aerial photography.

Radar can also provide information on lake ice and permafrost [9]. One aspect of the lake ice application which is of considerable importance is the development of a system for aiding navigation in the upper Great Lakes. In particular this involves the generation of techniques for estimating not only the location of ice buildings but also for estimating the thickness of ice. Thus this application falls under both the parametric and contextual applications areas. With respect to the permafrost application, radar imagery would be employed for the location of the permafrosted areas. Using the radar imagery, base maps could be constructed for reference during the planning stages of construction and mineral exploration.

For these applications very little information is available indicating suitable choices of radar parameters. Perhaps most important, though, particularly to the cartographer, is a high degree of geometric fidelity. Moreover for certain applications such as those involving industrial regulation, a high degree of spatial resolution can become paramount.

5. SYSTEM RESTRICTIONS AND SPECIFICATIONS

While the task of specifying the parameters of a radar system which are amenable to all users of the system is not easy, the task is further complicated by the fact that the system designer must also be satisfied. The design task of systems with large off-nadir angles and/or large elevation beamwidths for example, can be particularly troublesome. While many considerations limit the off-nadir angle and angular range over which a radar may operate, two fundamental factors which have to be taken into consideration are ambiguities and transmitter power requirements. This is particularly true for a synthetic aperture system operating from orbital altitudes. While these considerations may at first glance seem to be uncoupled effects, they are indeed highly dependent upon one another. For example, as attempts are made to increase angular range, the pulse repetition frequency is in general decreased to avoid ambiguous range returns. At the same time, the pulse repetition frequency must be maintained high enough to avoid azimuth ambiguities. These considerations may be further complicated if it is desired to operate at large off-nadir angles. For a fixed average transmitter power the pulse repetition frequency must in general be decreased to allow higher peak power, necessary for maintaining required signal-to-noise ratios.

Constructing a system to operate at frequencies higher than about 9 or 10 GHz is also difficult. This is a result of the fact that extremely high tolerances are called for in the construction of a suitable antenna system. Because these tolerances are expressed in terms of

signal wavelength, higher frequencies (shorter wavelengths) result in absolute tolerances often too small to be held by the most expert machinist. The Hughes Corporation, for example, in their study [5] of the proposed shuttle radar noted that while the technical problems encountered in the design of a Ku-band antenna precluded operations at these frequencies, a 13 or 14 GHz antenna could be properly designed. It was noted, however, that a 13 or 14 GHz system would cost approximately 30% more than an X-band system.

The telemetry of data to earth stations can further compound the implementation of a spaceborne system if high resolution imagery is required over wide swath widths. An increase in swath width and image resolution quickly results in an overwhelming amount of data to be transmitted to earth. The result is that either more sophisticated onboard initial data reduction techniques are required to reduce the volume of data to be transmitted and/or that the telemetry bandwidths must be increased to accommodate the increase in data flow. Thus, given an upper limit on the telemetry time-bandwidth product a trade-off between swath width and resolution must be considered.

Upon receipt of the telemetered data it must undergo processing to produce the final imagery. Again a problem arises if a high resolution system is employed since processing requirements increase rapidly for even a marginal increase in image resolution. This is most true for a fully focused synthetic aperture imager in which case a modest reduction in resolution requirements results in a tremendous reduction in processor requirements. If it is determined that resolution must be sacrificed to decrease demands on the radar telemetry systems and processor requirements, a real aperture or unfocused synthetic aperture system may provide the resolution necessary. Not only would these systems ease processor and telemetry demands but they also represent a much simpler (particularly if a real aperture system is employed) and thus less costly alternative to a fully focused synthetic aperture radar. Table III presents a comparison of the ultimate along track resolution attainable with real aperture, unfocused synthetic aperture and fully focused synthetic aperture radars. For purposes of this example it is assumed that a dual frequency (10 GHz and 5 GHz) system, employing ten meter long antennas would operate from a 1000 Km altitude.

While the resolution advantage of the fully focused system is quite apparent, it is doubtful that a spaceborne radar would operate in such a fine resolution mode. More likely it would divide the maximum synthetic aperture into a number of subapertures and average the return in each subaperture to increase measurement precision. Nonetheless the requirements on the telemetry and processor systems would remain quite extreme. At the opposite extreme lies the real aperture imager. Since the telemetry and processor requirements for such a system are minimal, it is an attractive option if the degradation in image resolution can be tolerated. Moreover since none of the azimuth bandwidth is used for beam sharpening, the excess bandwidth is employed for increasing data precision. The third option is an unfocused synthetic aperture radar with resolution much better than a real aperture system but not nearly as fine as the synthetic aperture radar. As might be expected the telemetry and processor demands lie between the requirements made by the real and focussed synthetic aperture systems. However it should be stressed that the resolution shown in Table III would probably not be available on an operational basis since an almost mandatory increase in data precision requires a corresponding degradation in image resolution.

Each of these three options has advantages and, of course, serious drawbacks. In essence the choice among these three systems amounts to trading image resolution for easier processing and better data precision. Economics will undoubtedly have a large impact on the decision making process. However, perhaps more important factors to be considered are the requirements set forth by the users of the data.

Table IV summarizes sections 3 and 4 in that it lists the radar parameters most desired for a spaceborne radar. The first point to be noted is that for the applications listed, two systems are required. This is dictated not only by the relatively low frequency needed for soil moisture versus the higher frequency needed for snowpack, crop classification and contextual applications but also by the angular ranges for these same applications. While the lower frequency system is rather well defined, the higher frequency system, which has a broader range of applications, is not well defined. Moreover, as discussed earlier, the selection of 14.2 GHz as a desired frequency is not practical in terms of antenna construction. Thus it is apparent that a compromise is needed.

Table V presents one such compromise. The C-band (4.8 GHz) system has not been changed from Table IV. The X-band system, however, is now suggested for the remaining applications. The major compromise is reducing the frequency for crop classification from 14.2 GHz to 9.0 GHz.

This is a result of the costs involved in building a K-band antenna.

6. CONCLUDING REMARKS

Any attempt to specify baseline specifications for a system as sophisticated as a spaceborne imaging radar must at best be considered a compromise between user requirements and technical feasibility. Moreover the paucity of information concerning proper specifications for many (if not most) applications requires educated guesswork when the time comes for system definition. The suggestions presented herein are made in light of presently available information on target scattering properties. It is not implied that these specifications are optimum in light of all considerations. Rather, they should be thought of as initial best estimates of system specifications to be evaluated aboard a spaceborne testbed.

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TABLE I. MAS 1-8 and MAS 8-18/35 Nominal System Specifications

	MAS 1-8	MAS 8-18	35 GHz Channel
Type	FM-CW	FM-CW	FM-CW
Modulating Waveform	Triangular	Triangular	Triangular
Frequency Range	1-8 GHz	8-18 GHz	35.6 GHz
FM Sweep: Δf	400 MHz	800 MHz	800 MHz
Transmitter Power	10 dBm	10 dBm	1 dBm
Intermediate Frequency	50 KHz	50 KHz	50 KHz
IF Bandwidth	10 KHz	10 KHz	10 KHz
Antennas			
Height of Ground	20 m	26 m	26 m
Type	122 cm Reflector	46 cm Reflector	Scalar Horn
Feeds	Crossed Log-Periodic	Quad-Ridged Horn	----
Polarization Capabilities:	HH, HV, VV	HH, HV, VV	HH, HV, VV, RR, RL, LL
Beamwidth	12° at 1.25 GHz to 1.8° at 7.25 GHz	4° at 8.6 GHz to 2° at 17.0 GHz	3°
Incidence Angle Range	0° (nadir)-80°	0° (nadir)-80°	0° (nadir)-80°
Calibration:			
Internal	Signal Injection (delay line)	Signal Injection (delay line)	Signal Injection (delay line)
External	Luneberg Lens Reflector	Luneberg Lens Reflector	Luneberg Lens Reflector

TABLE II. Number of days necessary to reach a 90 percent rate of correct classification, as a function of observation period, τ , and sensor parameters. Figures are presented for both temporal segment 1 (s1; May 20 through June 26) and segment 2 (s2; June 27 through September 20).

Frequency, Polarization	$\tau = 5$ days		$\tau = 10$ days		$\tau = 15$ days	
	s1	s2	s1	s2	s1	s2
9.0, HH	x	30	x	80	x	x
9.0, VV	20	50	30	70	x	x
9.0, HH, VV	20	30	20	40	x	60
14.2, VV	20	30	20	50	30	45
14.2 HH, VV	20	30	20	30	30	45
14.2, VV; 9.0, HH	20	20	20	30	30	45

TABLE III. Comparison of the resolution capabilities of real aperture, unfocused synthetic aperture and focused synthetic aperture spaceborne radars.

Altitude 1000 km
Antenna Length 10 m

Local Angle of Incidence

Frequency (GHz)

Along Track Resolution

Real Aperture

Synthetic Aperture
(unfocused)

Synthetic Aperture
(focused)

10°		50°	
10	5	10	5
3.04 km	6.08 km	4.28 km	8.57 km
87 m	123 m	104 m	146 m
5 m	5 m	5 m	5 m

TABLE IV. Desired System Parameters for Parametric and Contextual Applications

A. Parametric Applications

<u>Application</u>	<u>Frequency Polarization</u>	<u>Angle of Incidence Range</u>
Soil Moisture Mapping	4.8 GHz HH, HV	7°-20°
Snowpack Wetness Mapping	> 8 GHz HH	>40°
Crop Classification	14.2 GHz HH, VV	40°-60°

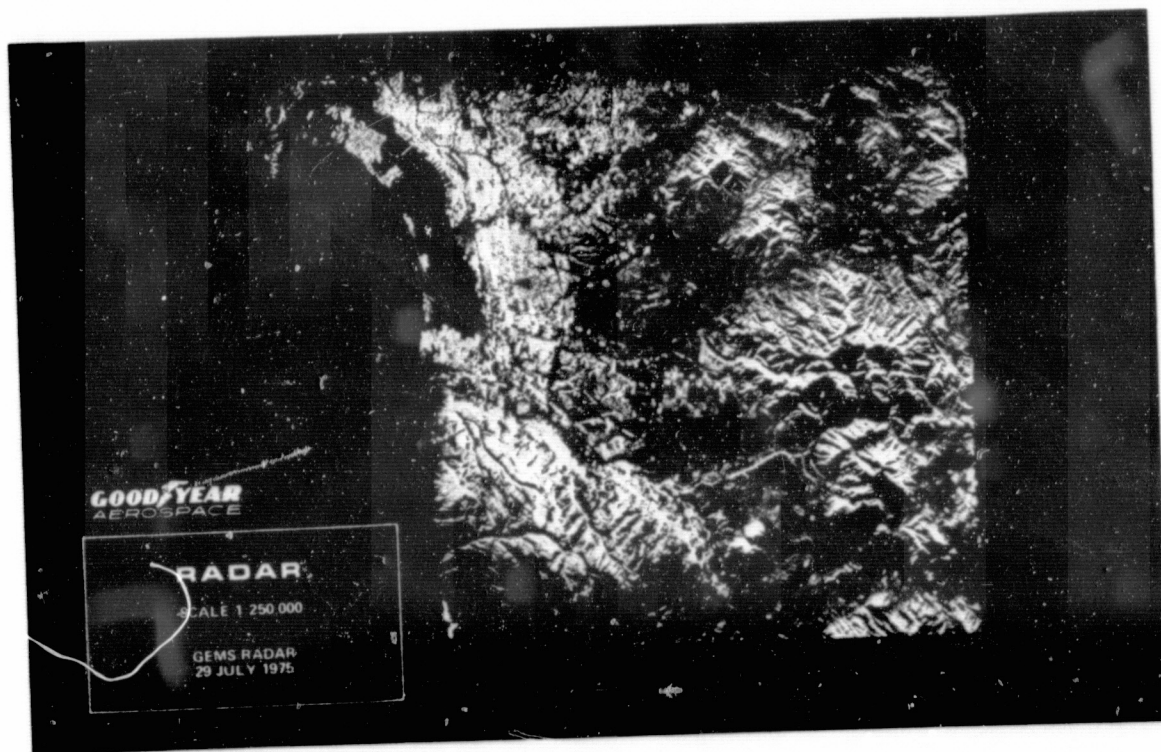
B. Contextual Applications

While it is not possible to be specific in defining system parameters for contextual applications, it is suggested that a dual polarized, X-band system operating at angles of incidence in the 40°-60° range would be suitable.

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TABLE V. Recommended Space Radar Parameters for Parametric and Contextual Applications

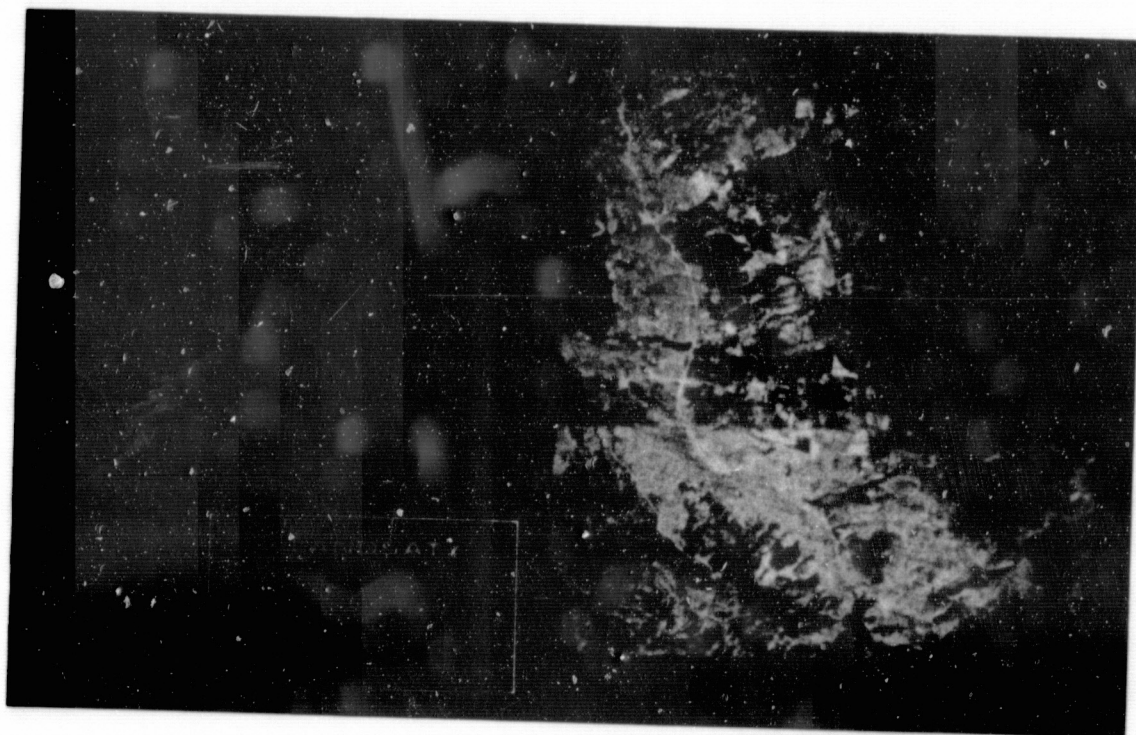
<u>Application(s)</u>	<u>Frequency</u>	<u>Polarization</u>	<u>Angle of Incidence Range</u>
A) Soil Moisture Mapping	4.8 GHz	HH, HV	7°-20°
B) Snowpack Wetness Mapping	9.0 GHz	VV, HV	40°-60°
Crop Classification			
Contextual Applications			



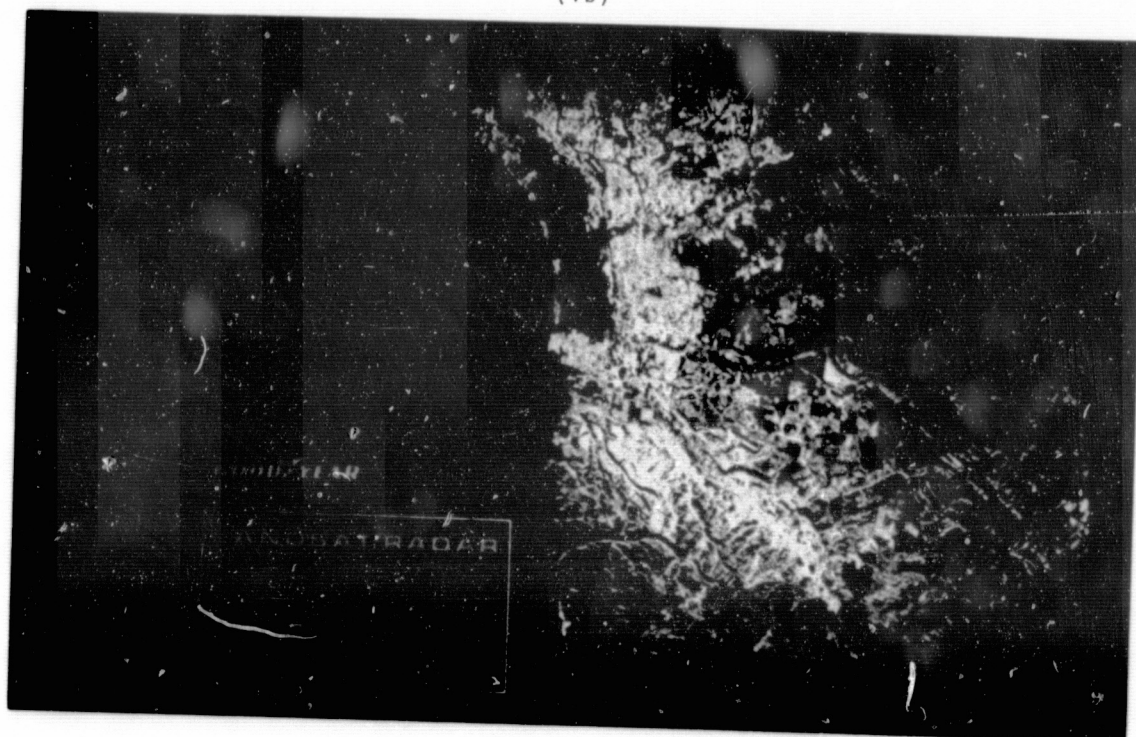
(1a)

FIGURE 1. Radar imagery (1a), LANDSAT color composite imagery (1b) and Radar/LANDSAT composite imagery (1c) of San Diego and surrounding areas.
(Courtesy of Goodyear Aerospace)

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(1b)



(1c)

WORLDWIDE SIDE-LOOKING AIRBORNE RADAR COVERAGE



FIGURE 2. World map depicting the areas (in grey) imaged by the GEMS radar.
(Courtesy of Goodyear Aerospace)

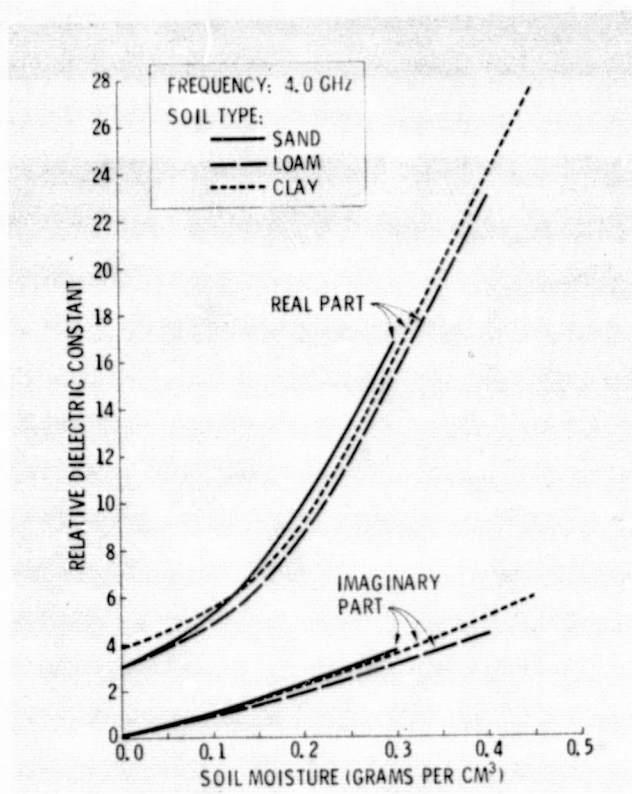
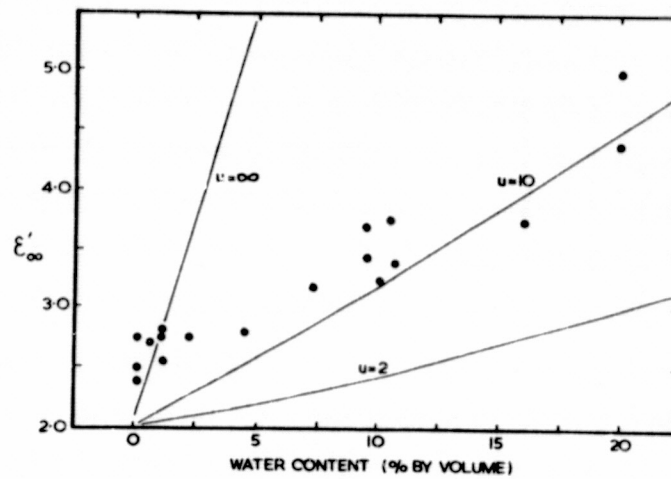


FIGURE 3. Representative variations of the dielectric constant of soils (3a) and snow (3b) as a function of water content. (The subscript ∞ on the ordinate label of 3b indicates high radio frequencies). 3b from [10]

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(3b)



FIGURE 4. Photograph of the MAS 1-8 system. The boom truck is the radar platform while the van contains control and data logging equipment.

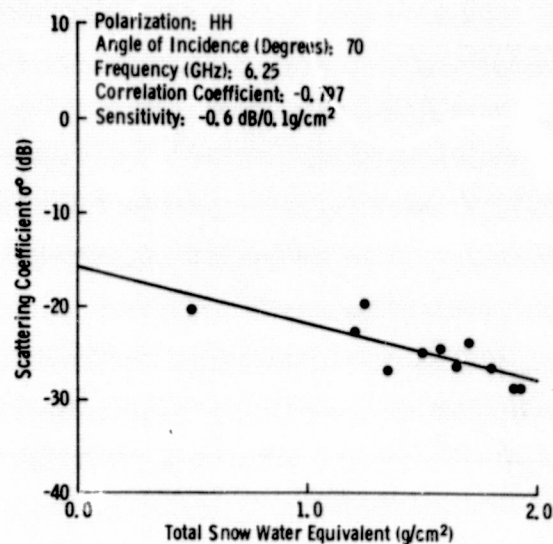


FIGURE 5. Variation of the scattering coefficient of snow versus total snow water equivalent. The line is a least squared error fit.

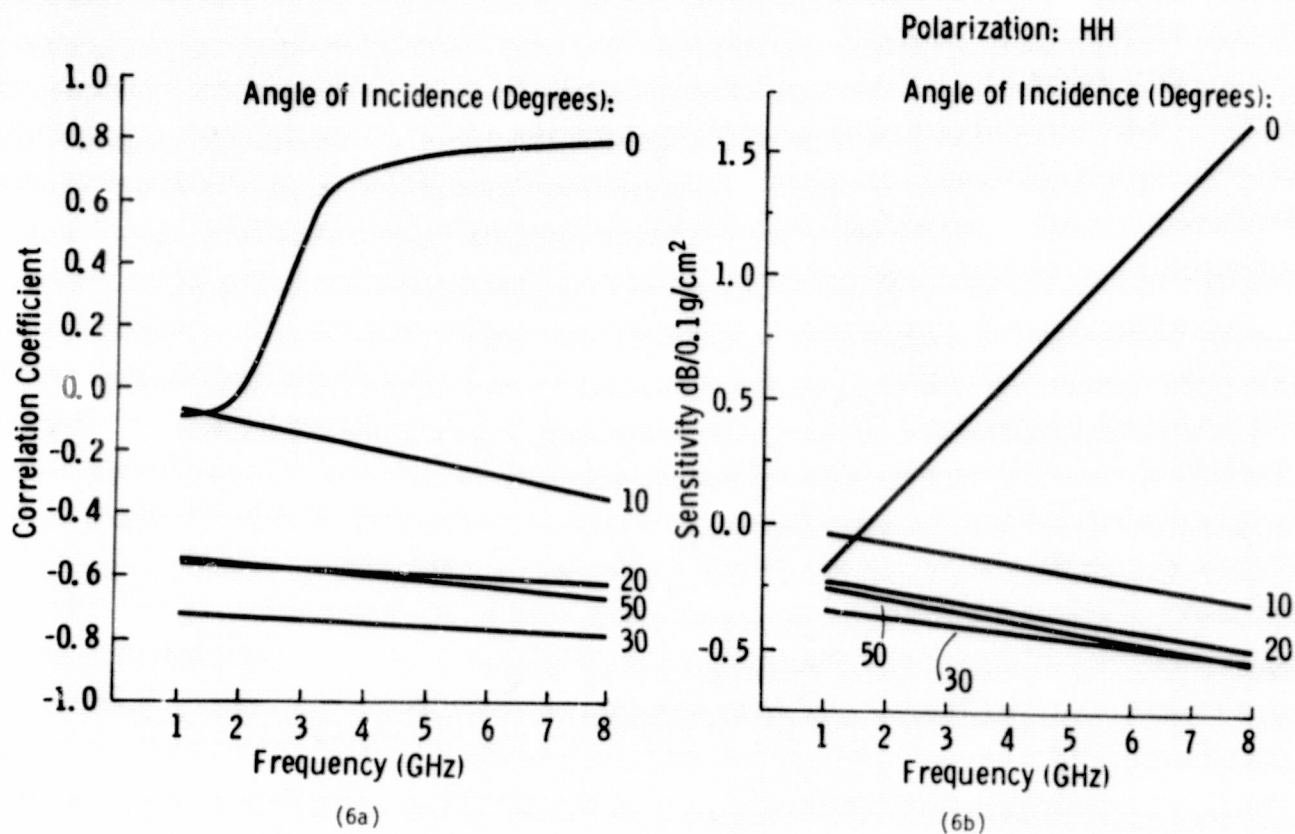


FIGURE 6. Correlation coefficients (6a) and sensitivities (6b) of σ^0 of snow water equivalent as a function of frequency and angle of incidence. The polarization is HH. Note the trend for the correlation to increase (in the negative sense) as frequency and angle increase.

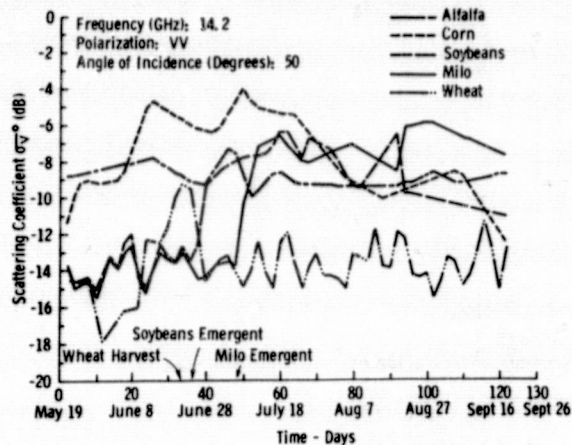


FIGURE 7. Temporal variations of σ_v^0 (dB) for five crop types.

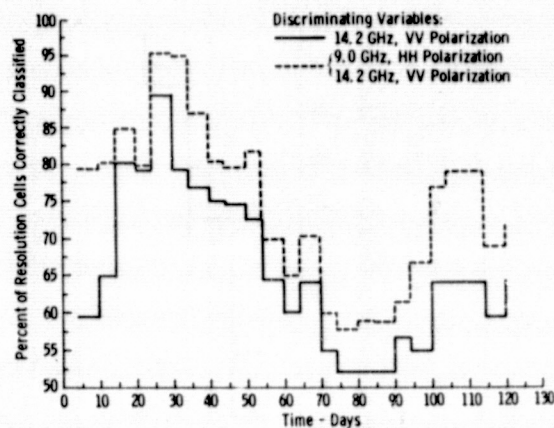


FIGURE 8. Comparison of daily classification results using single and dual frequency measurements.

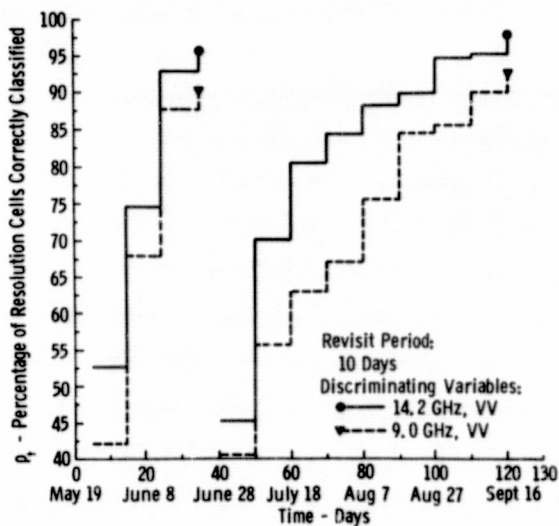


FIGURE 9. A comparison of p_t (14.2 GHz, VV) with p_t (9.0 GHz, VV) for a revisit period of 10 days. Note the clear superiority of the 14.2 data results.

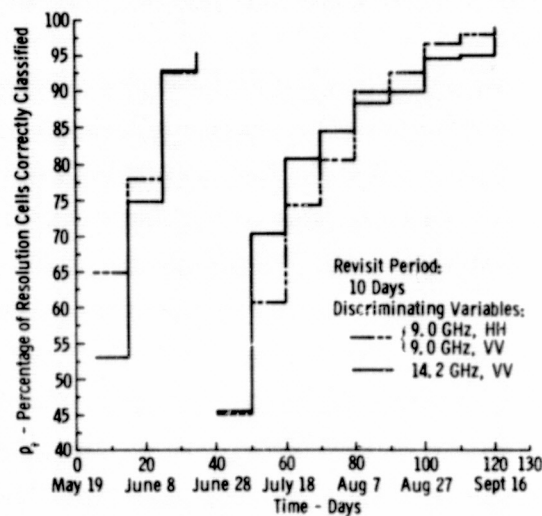


FIGURE 10. A comparison of p_t (14.2 GHz, VV) with p_t (9.0 GHz, HH, VV) for a revisit period of 10 days. The results are comparable for both sets of discriminating variables.

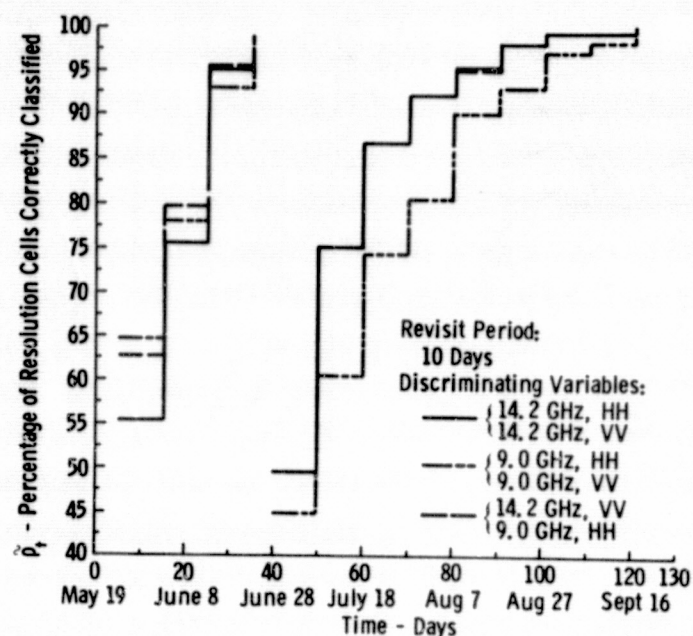


FIGURE 11. A comparison of $\rho_t(14.2 \text{ GHz, HH, VV})$, $\rho_t(9.0 \text{ GHz, HH, VV})$, and $\rho_t(14.2 \text{ GHz, VV, 9.0 GHz, HH})$. While $\rho_t(14.2 \text{ GHz, HH, VV})$, and $\rho_t(14.2 \text{ GHz, VV, 9.0 GHz, HH})$ are quite comparable with one another, $\rho_t(9.0 \text{ GHz, HH, VV})$ is clearly inferior to both $\rho_t(14.2 \text{ GHz, HH, VV})$ and $\rho_t(14.2 \text{ GHz, VV, 9.0 GHz, HH})$.

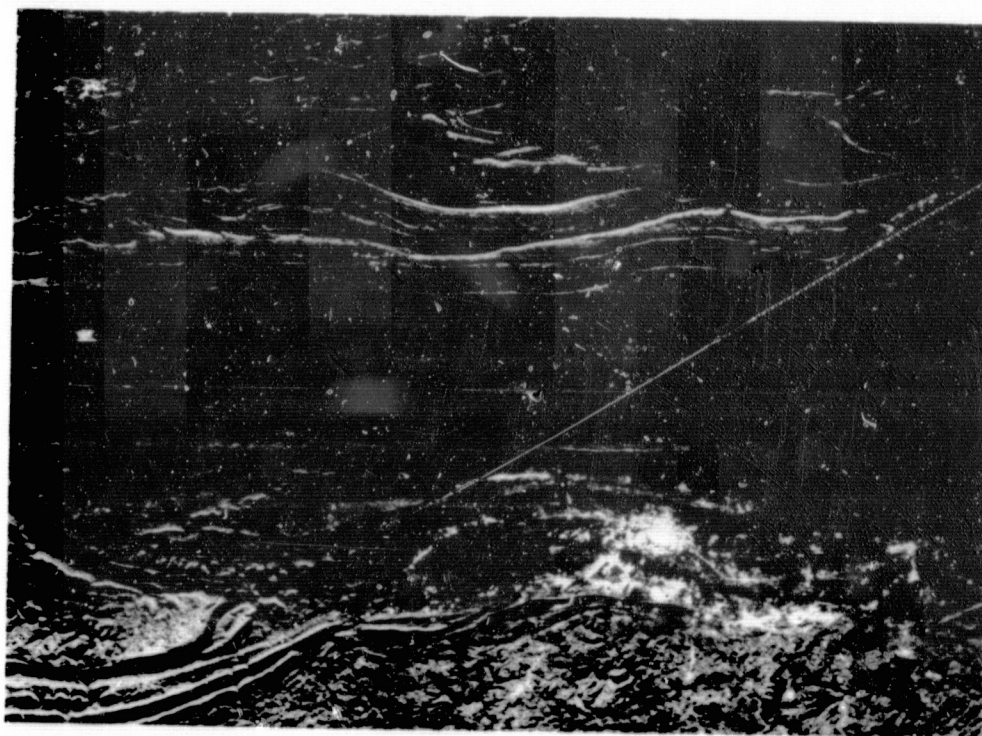


FIGURE 12. Motorola radar imagery of the Appalachian Mountains near Birmingham, Alabama (lower right). Note that the Motorola system images to both sides of the aircraft simultaneously.

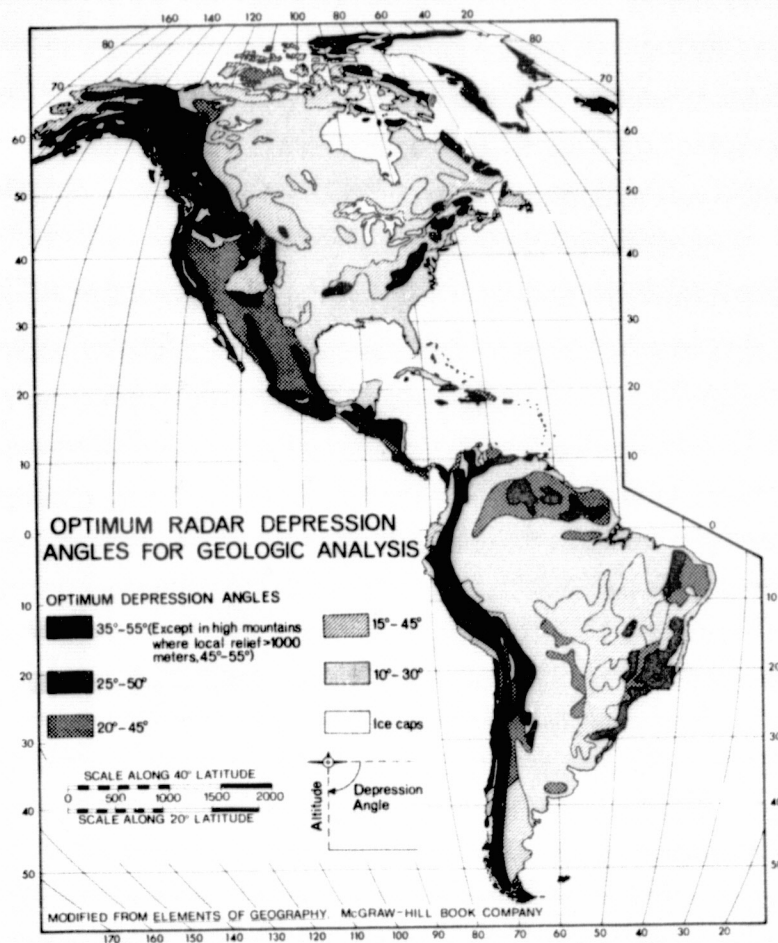


FIGURE 13. A portion of a map generated by MacDonald and Waite [6] which presents suggested radar depression angles for maximum relief enhancement.

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APPLICATION OF SYNTHETIC APERTURE RADAR (SAR)
TO REMOTE SENSING

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SUMMARY

During the past 20 years considerable effort has been directed at the research and development of airborne microwave imaging systems. A part of this effort, aimed largely at military applications in the U.S., has had as a major objective the realization of synthetic aperture radar (SAR) systems capable of fine resolution. As a result, images having fine resolution were generated and conventional photographic interpretation techniques were applied to extract information from these images.

More recently, with attention being directed toward the application of imaging systems to remote sensing problems, the imaging radar system has also been examined as a potential tool to obtain earth resource data. A wide variety of problems relating to the environment such as the measurement of sea state, ice monitoring, obtaining geological and hydrological information have been studied using radar imagery. Much of this work was done with imagery made at X- and K_a-band frequencies with radars originally developed for military uses. Investigators considering these various applications have shown that a multispectral approach is useful to improve the interpretability of the data. With a multispectral imaging radar system the contribution of the various parameters that affect the backscatter can be isolated. A common example is isolation of the effect of surface roughness for various wavelengths from effects due to the response to the surface electrical properties of the terrain.

Recently, an X-L band multispectral SAR has been developed especially for remote sensing and flown by ERIM. Data have been gathered for a large number of remote sensing applications and the usefulness of this instrument which produces four simultaneous images has been demonstrated. These applications include measurements of characteristics of fresh water and sea ice, obtaining images of ocean waves for wave spectra measurements, determining the characteristics of coastal zones and demonstrating the feasibility of using SAR for fishing vessel surveillance. Although much of the data obtained has not as yet been extensively analyzed and in some cases the corresponding ground truth is not adequate, the general conclusion is that a multispectral SAR greatly extends the utility of microwave imaging. A number of attributes of the terrain can be better deduced when images at two wavelengths and two polarizations are available.

Another important conclusion which results from the study of the data is that further research is necessary before the general utility of SAR is established and resources are committed to building operational instruments especially for use from satellite platforms. Some of these areas of research are:

(1) The concept of multispectral microwave measurements is based on the theory that each measurement at a different wavelength or polarization provides unique information about the nature of the scattering surface. In principle, a continuous measurement over the available electromagnetic spectrum should provide data to completely describe the scattering surface.

Such measurements are not practical due to both the expense and time required, but the use of additional channels at other wavelengths may provide measurements that will help in the interpretation for a number of types of SAR images. At the present time, the ERIM system has 3 cm and 23 cm operating wavelengths. It would be desirable to add a third channel operating at about 0.4 cm to obtain a measure of the scattering distribution of structure of a very fine scale. The addition of this short wavelength to the two existing wavelength channels would then provide measurements over a wavelength range of two orders of magnitude and would allow measurement of a true surface response, with no volume or penetration effects.

(2) Further study of the interaction between electromagnetic waves and various types of terrain elements is required. This should be done both through modeling of the interaction of electromagnetic waves with the terrain and through empirical studies of existing data and additional controlled flight experiments.

(3) The data which have been gathered have not been calibrated either relative to each channel nor on an absolute basis. Relative calibration will permit the comparison of the scattering coefficient between channels, an important capability which is required to validate models and to allow the development of automatic recognition techniques. More important, however, is an absolute calibration which will permit the determination of accurate values of scattering coefficients as a function of the SAR operating parameters, wavelength and polarization.

(4) Research is necessary in digital data analysis techniques which show promise of being able to extract additional information from the multispectral SAR data. Research should also be started on techniques which can be used to machine process and to apply automatic recognition techniques to the large amount of data which will be obtained from operational SAR sensors should they prove to have sufficient utility.

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LACIE: A LOOK TO THE FUTURE

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ABSTRACT

The Large Area Crop Inventory Experiment (LACIE) is a joint venture of the U.S. Department of Agriculture, the National Oceanic and Atmospheric Administration of the Department of Commerce, and the National Aeronautics and Space Administration. It is a "proof of concept" project designed to demonstrate the applicability of remote sensing technology to monitor globally an important world food crop - wheat. This paper discusses the need for more timely and reliable monitoring of food and fiber supplies, reviews the monitoring systems currently utilized by the USDA and United Nations Food and Agriculture Organization in the United States and in foreign countries, and elucidates the fundamentals involved in assessing the impact of variable weather and economic conditions on wheat acreage, yield, and production. The experiment's approach to production monitoring is described briefly, and its status is reviewed as of the conclusion of 2 years of successful operation. Examples of acreage and yield monitoring in the Soviet Union are used to illustrate the experiment's approach. A Look to the Future describes the LACIE transition program through 1981, consisting of an orderly transfer of proven technology from LACIE to an operational system within USDA, and to an expanded program that will culminate in the mid-to-late 1980's and which will adapt LACIE technology to the monitoring of other important food and fiber commodities. The needs and directions for a sustained level of research and development to support this global monitoring system are described.

ACKNOWLEDGMENT

The authors wish to acknowledge the many contributions to the planning and execution of this experiment by their colleagues not only in NASA but within the U.S. Department of Agriculture, the National Oceanic and Atmospheric Administration of the U.S. Department of Commerce, and the various participating universities and industrial research entities.

1. INTRODUCTION

The production of food and fiber has been a principal occupation of mankind throughout history. Produce from food and fiber crops is subject to large and irregular fluctuations. The within-year and year-to-year variations of the world's agricultural output are largely determined by factors beyond man's control. Although there is little hope of eliminating or even substantially

reducing these effects in the immediate future, reliable and timely global production estimates of food and fiber crops would permit informed planting and marketing decisions to be made early and in time to reduce the economic and social impacts resulting from major fluctuations in the global supply.

Research stimulated by private industry and the National Research Council in the late 1950's has led to the development of an initial base of technology for agricultural production monitoring. This base consists of Earth observation satellites, Earth orbiting meteorological satellites, communications links, high-speed computer processing equipment, mathematical models, and an initial understanding of the use of these components to monitor agricultural production. The Large Area Crop Inventory Experiment (LACIE) was initiated as a "proof of concept" project to assemble this technological base into a system and demonstrate its applicability to the global monitoring of the production of one of the world's most important food crops - wheat.

The fundamental elements of wheat production are wheat acreage, plant density within this acreage, the average number of heads per plant, the average number of kernels of grain per head, and the average weight of the kernels of grain. The LACIE survey approach utilizes models based on inputs from objective probability sample estimates which relate the above fundamental elements to the production in terms of average productivity, (bushels of wheat produced per acre) and total acreage. Landsat and, to a limited extent, meteorological satellites work with ground weather stations around the world to provide probability sample estimate inputs required by the LACIE models.

The experiment has been conducted, with considerable success, for 2 of its scheduled 3 global crop years. Results to date are quite encouraging and are a demonstration that cost-effective monitoring of global agriculture is a valid concept. The initial version of LACIE remote sensing technology has worked well and has provided more understanding of the factors which affect crop production estimates based on remotely sensed data. This improved understanding can be the basis of significant technological advances over the next few years and justifies continued attention to aid support for their development.

It will be necessary in the very near future to exercise considerable thought and to do extensive planning as to how the LACIE technological base is to be advanced. In fact, if the current and improved capabilities of LACIE are to be effectively exploited in the next few years and over the next decade, the need for effective planning is urgent.

2. THE NEED FOR GLOBAL AGRICULTURAL MONITORING INFORMATION SYSTEMS

Certain basic limitations of the planet Earth are becoming all too evident. Energy sources once viewed as infinite have been diminished to a level where their finite remains are understood and the need for their conservation is appreciated. Leaders of both industrial and developing nations are recognizing the planet's food production limitations, and there is increasing agreement that global agricultural planning is now a minimum requirement in assuring adequate food supplies. Global agricultural planning is of particular importance to the United States. The United States is the largest food exporter in the world and accounts for approximately one-half of the global grain trade (see table 1). In 1976, U.S. farmers produced agricultural exports, the estimated value of which exceeded \$22 billion. Without the contribution of the agricultural export market to the U.S. balance of payments in 1975, the United States would have suffered a deficit of over \$10 billion (fig. 1). The cash flow resulting from agricultural exports in 1975 accounted for a net positive balance of payments of some \$2 billion. Exports account for 20 percent of the U.S. gross farm income. Each year foreign markets take the harvest from almost 1 of every 3 acres harvested, or approximately 100 million acres of U.S. cropland. As a result, from not only the economic but also the humanitarian standpoint, the United States has taken a position that this country must do everything possible to maintain and expand its foreign agricultural markets.

As a major exporter, the United States must manage a delicate balance between supply and both domestic and foreign demand. The domestic consumption

of wheat in the United States is some 20 million metric tons per year. In 1976, U.S. farmers produced approximately 60 million metric tons of wheat. Although the depletion of these surpluses will depend largely on the size of this year's crop in the Union of Soviet Socialist Republics (U.S.S.R.) and possible shortfalls of production in Europe and the People's Republic of China, the anticipated U.S. export market of some 26 million tons will leave a significant carryover. Storage is costly and an abundance of reserves can lower the market price. Favorable weather in the 1975-1976 crop year created a USDA projection for a 1976-1977 decline in U.S. wheat trade and a leveling off of grain prices [1]. In 1976, prices of exported wheat declined from almost \$4 per bushel in January of 1976 to \$3 per bushel in January 1977, a decrease of 25 percent [2].

The relatively large U.S. wheat carryovers in 1976 were, in part, the result of its farm program being aimed at meeting increasing foreign demand. Since crop failures in the U.S.S.R. resulted in massive Soviet grain purchases from the United States in 1972 and 1973, total world grain acreage has increased about 8 percent and the world grain production has increased approximately 16 percent. The U.S. wheat acreage harvested for export has been increased some 16 percent since 1969. However, carryovers cannot be relied upon. Ever-increasing populations will require an ever-increasing food supply, leaving smaller reserves in the future (fig. 2).

In some years reserves have declined to a fraction of the historic demand. In 1974, world reserves dwindled to an amount equivalent to 27 days of consumption. In this situation, timely information relevant to anticipated supply is also crucial. Without reliable and timely crop demand and supply information, moratoriums on grain sales designed to protect our national interests can be costly, particularly if none is necessary. A case in point is the 1975 moratorium which, in retrospect, was unnecessary and caused foreign customers to turn to other more reliable markets and cost the U.S. farmer in export sales. Tradeoffs between reserves and costs must be made in accordance with both nationalistic and humanistic considerations. Such decisions would be greatly facilitated by timely and reliable information regarding global wheat supplies. It is this context of steadily increasing global demand and variable supply that has historically defined and more recently brought attention to the need for a global food and fiber monitoring system.

In addition to the economic factors discussed above, the major factors which influence the variability in the supply are meteorological factors such as drought and winter kill. Because these situations can develop at any period during the growing season, forecasts of both acres for harvest as well as yield and production will become more reliable for a region as harvest time nears. However, the significant factors affecting production also affect decisions to plant, germination, emergence, and acres removed from production. These impacts can be determined in some cases quite early in the crop year. For example, in the U.S.S.R., significant winter wheat acreage is often abandoned because of winter-kill. The decision to abandon this acreage and plant it as a summer crop or allow it to remain fallow is made in early spring. Because the northern and southern hemisphere regions are out of phase by 6 months, decisions to plant and to harvest wheat are being made at staggered intervals throughout the year (fig. 3). A global food information monitoring system could assess the impact on production of these meteorological situations and make them known in time to influence planting decisions in the United States, Canada and the exporting countries of the Southern Hemisphere. Such information could lead to an early establishment of realistic wheat price and so influence a variety of decisions.

In recent years, various organizations formed to study the world food situation have recognized this strong need for a global food and fiber monitoring system. In a report to the Congress by the Comptroller General of the U.S. General Accounting Office (GAO) [3], it was stated that "...Forecasts of wheat and corn acres harvested, yields, domestic demands, exports, carryovers and prices have not been sufficiently accurate in recent years. . .The Department (USDA) has taken some actions to improve its forecasting and GAO proposed others. . ." The World Food and Nutrition Study, National Academy of Science [4], made the following recommendation: "It is recommended that research be undertaken towards the development and implementation of a capability to repetitively monitor the status of the world's critical food producing regions and provide

early warning of potential shortages in production. It is further recommended that a continuing supporting research and technology program be organized to develop future improvements for later incorporation into subsequent versions of an initial monitoring system." A similar resolution for implementing an early warning system was made at the 1975 World Food Conference in Rome, Italy, in which an "urgent need for a world-wide food information system" was cited. It was recommended that such a system identify areas with imminent food problems and monitor world food supply and demand conditions. Specifically, it was recommended that "a global information and early warning system on food and agriculture" be established under the Food and Agriculture Organization (FAO) of the United Nations (U.N.); with initial emphasis on wheat, rice, coarse grains, soybeans, and livestock products.

While no comprehensive economic theory exactly quantifies the value of improvements resulting from improved forecast accuracies, an analysis of available global agricultural information and of the systems which produce the input agricultural statistics provides some insight into the question of the required performance of an improved and acceptable global information system.* World supply estimates are a compilation of country supply estimates generated for the most part by the various national agricultural information systems. The quality of world estimates, therefore, is a direct function of the quality of the systems in the various countries. The estimates from this conglomerate range from timely and reliable to nonexistent. Neither the U.S. Department of Agriculture (USDA) nor the FAO is in a position to generate sufficiently timely and reliable supply estimates for all commodities and countries where national systems are unreliable. All too frequently, estimates based on past trends, sometimes adjusted by judgment, are used in lieu of objective sources. Reports received from the USDA attache' network often end up being the primary source of foreign information for the USDA Agricultural system. This is not the primary mission of the attache' and few are specialists in the collection or analysis of agricultural data. The primary factors to be considered in evaluating a world information system are objectivity, reliability, timeliness, and adequacy in terms of coverage, efficiency, and effectiveness. "An ideal system would provide timely and unbiased interpretations of the current global situation and an outlook based upon estimates of known reliability for all commodities and countries through the use of the most cost effective procedures known to mankind."

A comparison can be made of the output of the FAO and the USDA, two organizations which currently operate world agricultural information systems. The USDA's world agricultural information system provides more timely information than that of the FAO. The statistical reliability of supply estimates is essentially the same, since both organizations rely largely on the data produced by national governments. The USDA releases estimates and assessments more frequently than the FAO. The Foreign Agricultural Service (FAS) and the USDA substitute their own estimates for politically biased "official" national estimates when necessary. To date, the USDA system has produced more timely assessments of the current situation and near term outlook while the FAO is steadily working to improve the reliability of the estimates of supply through its work with member nations to improve techniques utilized by the country. This qualitative analysis leads to the following summarization of the primary characteristics of currently available world agricultural supply estimates: (1) The objectivity of estimates is largely a function of the objectivity of the estimates released by the host government. (2) The reliability of the estimates is largely a function of the methods used by the nation to collect agricultural statistics and to assess them. This varies significantly from country to country. (3) Most national systems rank poorly in terms of timeliness of estimates of supply. (4) Adequacy is impaired by lack of uniformity of reporting both in terms of content and geographic coverage from nation to nation. (5) The efficiency and effectiveness of most national systems requires significant improvements.

*The following review of the state of the current world agricultural information system and required improvements is in large based on the work of John Schnittker Associates as reported by Howard W. Hjort while a Vice President and partner of the firm; H. W. Hjort currently serves in the USDA as the Director of Agricultural Economics.

The characteristics of current world agriculture supply impose profound limitations on the accuracy of the current systems, not likely to soon be resolved.

A more quantitative analysis can be made of the quality of these world supply estimates if the above-mentioned limitations are kept in mind. The most accurate and timely estimates are made for U.S. agriculture. The Statistical Reporting Service (SRS) of the USDA utilizes probability surveys of acres planted, acres harvested, and the average productivity and yield from acres harvested. For example, winter wheat production estimates are made in December and May and every month thereafter through harvest until the following December. A final estimate for that crop is then made the following December — 1 year later. The SRS periodically sends questionnaires to more than 100 000 U.S. farmers and follows up with actual farm visits to survey more than 16 000 randomly selected sample sites. While these estimates are quite accurate at the national level, the statistical design does not permit such high accuracies at state levels and below. An analysis of historic SRS survey forecasts of wheat production in comparison to the SRS final survey estimates indicates that at the national level, early in the season, and prior to June 1 (roughly the heading to maturity period for U.S. winter wheat), the SRS forecasts of wheat production were within ± 10 percent of the final estimates in about 85 percent of the years from 1966 to 1975. The SRS estimates made after July 1, at harvest, were within ± 2 percent of their final figures.

To obtain such accurate estimates at the state levels and below would greatly increase the expense of the existing SRS forecast system. As an alternative, SRS is currently investigating the use of Landsat data as a cost-effective means of making accurate estimates at the lower geographic levels [5].

Historically, estimates for foreign nations are much less accurate than estimates for the United States. The most accurate of the estimates for foreign countries are those for Australia and Canada, the other two major wheat exporters, with the USDA at-harvest estimates of Canadian wheat production being within ± 10 percent of the final Canadian figures in about 90 percent of the years from 1966-1975. In Australia, the USDA at-harvest estimates were within ± 10 percent in only 80 percent of the same years. In both countries, however, the preharvest estimates are much less accurate. USDA preharvest estimates of wheat were within ± 10 percent in roughly one-half the years in Canada and in about one-fourth the years in Australia. The estimates for the wheat crops of two major importers, the U.S.S.R. and India, were less reliable. The USDA at-harvest estimates of wheat were within ± 10 percent in only about one-third of the years in the U.S.S.R. and somewhat over one-half the years in India. In most foreign countries, the very-early-season estimates are within ± 10 percent in about 25 percent of the years.

The frequency and magnitude of these early-season-to-harvest differences can be explained in part by the fact that the estimates assume in early season that historic trends in weather and planting patterns will prevail. Generally, these estimates are based on reports by foreign governments of planted acreage and the historic value for average yields. Because the weather patterns differ so widely from year to year, the chance in any one year for weather conditions being very near the average (or normal weather) is not very large. Because acres planted, the fraction of acres actually harvested, and the resulting yields from the acres harvested are so critically dependent on weather patterns, there is a correspondingly small chance that actual acreage, actual yield, or actual production will be very close to average or normal values.

This leads then to a discussion of the precise manner in which government policy, economics, and variable weather patterns affect the acreage planted, the acreage harvested, and the average productivity of the harvested acres; i.e., *yield* for harvested acres. As a first step in this discussion, it is wise to review a bit of terminology, since often the term *yield* is used interchangeably with *production*; in addition, the term *acreage* must be carefully defined as to whether planted acres or harvested acres are being discussed. In crops such as wheat, the quantity of interest is tonnage produced from acres actually harvested. Acreage planted but not harvested (abandoned) for one

reason or another, will produce some grain, but of course will not contribute in the market place. *Yield for harvested acres* is defined as average productivity for the acres harvested. *Yield for planted acres* is defined as the production from *harvested acres* averaged over all planted acres. In contrast, *biological yield* is the potential average production from all acres planted, including the lower yields from those acres abandoned.

In existing reporting systems, the quantity of importance is production. However, these reporting systems all make separate estimates of acreage planted and acreage harvested, as well as yield, and use these estimates of the components of production to estimate production. In other words, production is inferred from individual estimates of acreage and yield. Weather is extremely variable over a geographic region; western Oklahoma may be relatively dry while the eastern half can be experiencing favorable conditions. To get an acceptably accurate forecast of production, it is critical to associate the right weather with the actual acreage being affected. Where the effects are so severe as to remove acreage from production as in the case of winterkill or severe drought, this reduced acreage must be accounted for. In the highly accurate domestic system utilized by SRS, this is accomplished through stratification of the United States into subregions (strata) over which the areal density of agriculture is rather uniform. Within each stratum, samples of acreage are chosen at random for estimates of the acreage A_i harvested within the i th stratum and the average yield Y_i for the harvested acres. Since Y_i is the average productivity for this stratum, Y_i is given by

$$Y_i = P_i / A_i \quad (1)$$

where P_i is the production harvested from that stratum. Given then that Y_i and A_i can be estimated for each stratum in the United States, the production P_N from all harvested acres in the United States is given by

$$P_N = \sum_{\substack{\text{strata} \\ \text{in U.S.}}} Y_i \cdot A_i \quad (2)$$

In addition, SRS publishes what is called an average yield Y_N for the United States. This average yield is defined, at least in principle,* in the same manner as it is defined at the stratum level; i.e.,

$$Y_N = P_N / A_N \quad (3)$$

where A_N is the total acreage harvested in the United States. In terms of the yields Y_i and the harvested acres A_i observed at the stratum level, Y_N becomes an acreage weighted average of the stratum level yields. This can be seen by substitution of equation (2) into equation (3)

$$Y_N = \sum_{\substack{\text{strata} \\ \text{in U.S.}}} (A_i / A_N) Y_i \quad (4)$$

From equation (4) then it can be seen that the yield for a country or a region composed of strata, cannot be estimated independently of the distribution of harvested acreage within the country. That is, given the forecasts of yield $\{Y_i\}_{i=1}^n$ for the n strata within a country, one cannot estimate the yield for the country without also knowing the distribution $\{A_i\}_{i=1}^n$ of harvested acreage within the country. The physics of these facts can be demonstrated by considering an example of a region consisting of two subregions as shown in the example following. In this simple example, suppose the left half of the region κ ,

*Acreage and yield estimates from the SRS probability survey are for various reasons modified based on information acquired from nonprobability surveys prior to their release. In certain cases Y_N and P_N may be the independent variables with A_N adjusted to agree with the ratio of P_N to Y_N .

Stratum 1 Yield = 15 bu/acre	Stratum 2 Yield = 30 bu/acre
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Region R composed of two subregions.

stratum 1, has had rather uniform weather and therefore uniform yield, whereas stratum 2 has had uniform weather also but different yield than that experienced in stratum 1. Suppose further that the growing conditions have generally been better in stratum 2 than in stratum 1 so that y_1 is 15 bushels/acre whereas y_2 is 30 bushels/acre. Now, suppose that a total amount of acreage A is harvested in the region R. Question: How much wheat is produced from R? In fact, the question cannot be answered by knowing only the total acreage A harvested in the region. In addition, the manner in which A is distributed within the region must also be known. For example, suppose the acreage harvested from stratum 1 is 10 000 acres and is twice that harvested in stratum 2; i.e., 20 000 acres. The production realized from 30 000 total acres for R will then be

$$P = A_1 y_1 + A_2 y_2 = 10\,000 \times 15 + 20\,000 \times 30 = 750\,000 \text{ bushels} \quad (5)$$

and the average yield for the region would have been

$$Y_R = 750\,000 \div 30\,000 = 25 \text{ bushels/acre} \quad (6)$$

However, suppose the opposite planting and harvesting pattern had been realized under the same growing conditions. That is, while stratum 1 still had growing conditions conducive to a yield of 15 bushels/acre and stratum 2 had growing conditions conducive to 30 bushels/acre, 20 000 acres were planted and harvested in stratum 1 and 10 000 acres were planted and harvested in stratum 2. Then the total production for the region R would have been only

$$P = 20\,000 \times 15 + 10\,000 \times 30 = 600\,000 \text{ bushels} \quad (7)$$

and the average yield would have been

$$Y_R = 600\,000 \div 30\,000 = 20 \text{ bushels/acre} \quad (8)$$

Thus, from this simple example and the relation expressed in equation (4), it can be seen that the estimate of yield at a country level is directly dependent upon the geographic distribution of acres actually planted and then harvested. Therefore, not only must a survey system monitor the total acreage harvested, it must also monitor the geographic distribution of the acres harvested as well as the associated geographic pattern of weather and other growing conditions. In addition, the economics of the region for which planting and harvesting decisions are being made can also affect the average yield since economic factors to a large extent determine the minimum value of the yield for a field which the farm operator makes a decision to abandon (i.e., not harvest the field). In other words, the poorer the weather, the more likely it is that the planted acreage will be abandoned; however, the decision to abandon will be based to some extent on the cost of harvesting in comparison to the benefits of doing so.

Thus, in addition to the factors discussed earlier, the average yield for harvested acres is critically dependent upon the degree of abandonment. In a region with a marginal crop, the average yield per harvested acre would be lower if the farm operator decided to harvest all acres than if a decision were made to simply abandon the acreage with lower yields. These facts forge an inseparable link between yield and acreage and require a monitoring system which monitors both.

3. LACIE, ITS PURPOSE AND ACCOMPLISHMENTS

3.1 EXPERIMENT OVERVIEW

The Large Area Crop Inventory Experiment (LACIE) was initiated in 1974 as a "proof of concept" experiment to assimilate remote sensing technology developed

over the previous decade, apply a resultant experimental system to the task of monitoring a singularly important agricultural commodity over the world, modify the approach as necessary and conceivable and, finally, demonstrate the technical and cost feasibility of global agricultural monitoring systems.

The roots for LACIE were carefully and intentionally established in 1960 when the Agricultural Board of the National Research Council recommended that a committee be formed to investigate the potential of aerial surveys to provide an increased capability to monitor agricultural conditions over large geographic areas. A group of interdisciplinary scientists was selected to serve on the Committee on Remote Sensing for Agricultural Purposes and by late 1962 had designed experiments to indicate the feasibility of utilizing multispectral remote sensing to monitor the production of important agricultural commodities. An organized research program was established by the USDA and the National Aeronautics and Space Administration (NASA) in 1965 that led in an orderly fashion from the first successful computer recognition of wheat using multispectral measurements collected with aircraft in 1966 to: (1) the identification of the spectral bands and other design characteristics of the first Earth Resources Technology Satellite (ERTS) in 1967, (2) a simulation of ERTS* data from the S065 multispectral photographic system of Apollo IX in 1969, (3) the successful launch of ERTS in 1972, (4) and the successful feasibility investigations in 1972, 1973 showing the utility of the ERTS system to monitor important agricultural crops, and (5) the design and initiation of LACIE in 1973, 1974.

LACIE was designed to estimate on an experimental basis wheat production over important producing regions of the world. Timeliness and accuracy goals were established in recognition of the essential requirements for global agricultural information. The experiment was designed to establish the feasibility of acquiring and analyzing Landsat data within a 15-day interval. Importantly, the at-harvest estimates were to be within 10 percent of the true estimate at the national level 90 percent of the time. An additional performance goal was to determine how early in the crop year estimates could be produced and with what accuracy and repeatability. Additionally, the estimates were to be made with repeatable and objective procedures. Qualitative judgments were to be kept to a minimum. The experiment was scheduled to be conducted in three phases:

- (1) In Phase I, the technology to estimate the proportion of regions planted to wheat would be implemented and tested, and similarly the technique to estimate the yield from specific acreages would be developed and tested.
- (2) In Phase II, the technology as modified during Phase I would be further tested over expanded geographic regions and modified as required.
- (3) In Phase III, the modified technology would be tested and evaluated over a still wider range of geographic conditions.

The experiment was made of three major elements:

- (1) A quasi-operational element to acquire and analyze Landsat and meteorological data to make experimental estimates of production.
- (2) An off-line element to test and evaluate alternative approaches as required to meet the performance goals of the experiment, and
- (3) An element to research and develop alternative approaches.

The experiment has been jointly conducted by personnel from NASA, USDA and NOAA (National Oceanic and Atmospheric Administration) of the DOC (Department of Commerce). They represent the many disciplines including physics, plant pathology, engineering, agronomy, statistics and mathematics, soils sciences, economics, and plant physiology, important to meeting the objectives of the experiment.

*The ERTS satellite was renamed Land Satellite 1 (Landsat 1). A second earth resources satellite Landsat 2, identical to Landsat 1 is now in orbit.

The major components of the quasi-operational element of the experiment include the Landsat and its acquisition and preprocessing subsystems, the World Meteorological Organization (WMO) weather reporting system, the NOAA development and operational facilities in Washington, D.C., and Columbia, Missouri, regions and the analysis, compilation and evaluation activities at the NASA Johnson Space Center (JSC) in Houston, Texas. The experiment also draws significantly on the expertise of university and industrial research personnel.

Because of the complexity and importance of LACIE, periodic technical reviews have been held where invited experts have reviewed LACIE results have discussed specific technical issues and have made specific recommendations. This process has made significant contributions to LACIE.

3.2 THE LACIE TECHNICAL APPROACH

The LACIE approach utilizes the direct observational capabilities afforded by Landsat together with estimates of weather variables to estimate production. This approach requires that each geographic subregion (selected to be relatively homogeneous with regard to wheat acreage and yield) in a country be monitored to (1) forecast the quantity of wheat acres available for harvest (both winter and spring individually in each subregion), and (2) to forecast the expected productivity for each subregion (yield) of the acres available for harvest. The total wheat production for each subregion is then obtained by the product of available acres for harvest and yield for harvested acres. The production forecasts for all subregions are then summed to obtain the country-level forecast as in equation (2). In addition, the subregional forecasts of acres for harvest are summed to obtain a forecast of national acres for harvest. An average yield for all acres harvested nationally is then obtained, which is by definition the acreage weighted average derived in equation (4). This acreage weighted average yield is a desirable estimate to have since, when multiplied by the national acreage, it will reproduce the national production estimate. The LACIE stratification and sampling approach shares similarities with the domestic approach utilized by the timely and accurate SRS survey system. The approach has also been adopted by the Canadian government and other national governments.

Within each of the subregions described in the opening paragraph, Landsat multispectral data is collected each 18 days from selected 5×6 n.mi. segments randomly drawn from each stratum. Within each segment, wheat is distinguished from non-wheat by monitoring the temporal development of each field from wheat planting through harvest. The areal percentage of wheat in each segment in the stratum is then estimated and thereby an average percent for the stratum can be determined. The average areal percent wheat can then be multiplied by the total agricultural acreage* in the stratum to estimate total wheat acres for the stratum.

As an example of the information contained in the sequential Landsat coverage consider the sequence of imagery shown in figures 4a, 4b, and 4c. This imagery was acquired over a LACIE 5×6 n.mi. segment located in Sherman County in the northwest corner of Kansas. Annotated on this sequence are selected wheat and non-wheat fields. Note that as the wheat begins to emerge, it appears on the color-IR imagery (computer generated from digital magnetic tapes) as a pink response indicating the increasing reflectance in the near infrared channel monitored by Landsat. Following winter dormancy, the February imagery indicates that all fields have survived the winter without loss to winterkill, although there is some bare soil spottiness in several of the fields. Note in the March, June, and July images the wheat is of varying degrees of vigor. Some fields are quite pink in the image indicating vigorous growth, while others are quite mottled indicating large areas with little or no vegetative cover. In the July 1 image, harvesting has begun in the outlined circular field (left center of image). In the final image acquired only 18 days later, the harvesting of wheat is almost complete as indicated by the bright signature and none of the fields appear to have been abandoned. In addition, the spring crops which had begun to emerge in mid-June are now quite vigorous on the image.

*Stratum agriculture is delineated on full frame Landsat imagery and planimeted to determine total agriculture acreage within stratum. Agriculture is defined to be any area of the image for which field patterns are evident.

From this sequence the following characteristics of the Landsat estimates of harvested wheat acreage can be noted: (1) It is both the spectral differences over time and at any one time between wheat and other crops which permit wheat to be identified and its acreage estimated. The estimates are made for wheat that is emerged and detectable. (2) Wheat areas subjected to weather conditions so harsh as to result in disappearing acreage, such as represented by areas of bare soil or extremely sparse vegetation in Landsat data, will not contribute to the LACIE estimate of wheat acreage and thus will reduce the LACIE estimate of production. In this way Landsat data accounts for severe conditions in the production estimates. (3) Landsat data can be used to monitor abandonment. For example, if a field identified in the early winter (November-December) time-frame does not re-emerge following dormancy in January-February, acreage loss to this factor can be identified. (4) In early season, LACIE estimates only the detectable (pink) wheat acreage as opposed to planted wheat acreage. Generally, a minimum of 20 percent ground cover is required before wheat acreage is detectable. As the season progresses, the wheat acreage detectable by Landsat will increase and converge in early season, following complete emergence, as will the LACIE wheat acreage forecast, to the total standing* acreage potential for harvest.

As a remote sensing system such as LACIE begins to develop an image data base with several years of data, the estimates of acreage will become increasingly accurate and additional information can be gathered regarding potential yield. Consider, for example, the two-year sequence of Landsat imagery acquired in the Saratov region of the U.S.S.R. as shown in figures 5 a and b. Figure 5a displays the sequence of imagery acquired in the 1974-1975 crop season and the identities of the outlined fields. In figure 5b is the sequence for 1975-1976 crop season. From this multi-year sequence we can see the effect of the crop rotation patterns. The fields labeled 1 and 2 were fallowed in 1974-1975 and were planted to spring (field 1) and winter (field 2) grains in the 1975-1976 crop year. Field 3 which had the characteristic winter grain development cycle in the 1974-1975 sequence has been planted into a row crop (possibly corn or sunflowers) for the 1975-1976 crop season. In addition fields 4, 5, and 6 show rotation patterns respectively, of winter grains (75) to winter grains (76), spring grains (75) to winter grains (76) and winter grains (75) to spring grains (76). Since rotation patterns are known to affect productivity of the fields, it can be easily seen how multi-year spectral data contains information related to crop yield.

There is, in addition, within any one year, potential information in the spectral data related to crop condition and thus yield. Note in the 1974-1975 sequence of the Saratov segment that the apparent vigor of the fields declines drastically from the May 21 image to the June 8 image. In this year, this particular area was undergoing a significant drought. The impact of no moisture is clearly evident on this detailed image, as it is in the two full-frame images of figures 6 and 7 acquired in this same area in the U.S.S.R. Note the image of figure 6 which was acquired in the 1975-1976 crop year with adequate soil moisture and then the image acquired over the same area one year earlier. The lack of vigorous response in the 1974-1975 image is indicative of the serious moisture shortage.

As of this date, the Landsat multispectral data cannot be used to completely quantify the reduction on yield of soil moisture deficiencies and other such episodic events which affect the spectral reflectance. Of course, if such events are severe enough to cause abandonment of acreage, this could be detected in the Landsat data and the resulting decrease in the acreage estimate would decrease the estimate of total production. At the present time, the spectral data is used only to monitor the geographic extent of the episodic events and the regular LACIE analyses are used to quantify the impact of these events on yield and production [6, 7]. Research efforts are underway to utilize the spectral data directly to estimate yield.

*By way of contrast most existing systems measure total field acres including bare spots. Generally total field acres will exceed standing acres.

Another very important way in which the spectral data contributes directly to the estimation of production is by monitoring year-to-year fluctuations in total acreage. Apparent from the multi-year image sequence of figures 5a and 5b is the fact that there are significant changes in acreage from year to year within a segment. As discussed in the first section of this paper, such changes affect yield also. In addition to these shifts, however, there has been in recent years a steady expansion of area under cultivation in the U.S.S.R. This trend is indicated in one full-frame image sequence of figures 8 and 9 acquired over the Kustanay oblast, U.S.S.R., in May 1973 and two years later in May 1975. At the scale of the full-frame image the upper finger of agricultural land can be seen to be much larger in 1975 than in 1973. At a detailed segment level segments 8243 and 8224 both show significant increases as a result of U.S.S.R. expansion in the new lands.

Returning to the manner in which acreage estimates are made for each LACIE segment, the temporal and spectral information described earlier is used by an analyst to identify several blocks of data within the 5×6 n.mi. image as either wheat or non-wheat. These blocks of data called training areas, are then submitted to the computer which reads the digital magnetic tapes and estimates the statistical distributions (probability density functions $f_w(\bar{X})$ and $f_o(\bar{X})$) of the radiometric (Landsat pixels) measurements $\bar{X}$ acquired within the wheat and non-wheat training areas. The radiometric measurements recorded for the non-training area portion of the segment are automatically classified as wheat or non-wheat by a machine processing algorithm which computes the likelihood that the radiometric value $\bar{X}_i$ of each pixel is representative of the distribution determined for wheat $f_w(\bar{X}_i)$ and for non-wheat $f_o(\bar{X}_i)$. $\bar{X}_i$ is classified as wheat if it is more representative of wheat, i.e., $f_w(\bar{X}_i) \geq f_o(\bar{X}_i)$. Otherwise $\bar{X}_i$ is classified as non-wheat. These probability density functions are more commonly referred to as signatures. The end result of this manually-aided machine analysis is an estimate of what fraction of the total Landsat pixels within a segment corresponded to wheat. This fraction is then assumed to represent the correct areal percentage of wheat contained by the 5×6 n.mi. segment. Figure 10 is a display of a classification map of the April 26 Saratov segment shown in figure 5b. The grey picture elements are those Landsat measurements which the computer classified as wheat. The infrequently occurring black elements represent Landsat measurements which were dissimilar from all of the measurements recorded over the training areas. All other crop classes are represented as white.

The errors associated with this technique derive from the fact that certain other crop types mimic wheat, both in its growth cycle and its appearance at each time in the growth cycle. Such crops are called confusion crops. In addition, the Landsat spatial resolution of approximately 1.1 acre, introduces error in measurement on field boundaries, particularly in agricultural regions which have field dimensions on the order of Landsat's resolution. Results of LACIE to date have indicated that the major confusion crops to wheat are certain small grains, particularly spring barley and winter rye. In sub-regions where these confusion crops are in appreciable abundance, LACIE has identified total small grains and reduced these estimates to wheat estimates using historic relative abundance figures for these crops to wheat. These will be discussed in more detail in the results section.

The yield for harvested acres is forecast in LACIE through the use of regression models which utilize weather-related variables obtained from the ground-based stations of the WMO network. These models [8, 9, 10] are referred to as agrometeorological models. The first generation models currently used in LACIE are developed around monthly averages of temperature and precipitation. In the United States Great Plains yardstick area there are both winter and spring wheat models, covering the 12 areas designated in figure 11. The yield and climatic data base used to derive the U.S. models is approximately 45 years in length. The yield data is obtained by aggregating the USDA/SRS estimates of harvested acreage and production to obtain yield in bushels per harvested acres, individually, for both winter and spring wheat, in each of the 12 subregions. The climatic data consists of monthly climatic division averages of precipitation and temperature. These averages are weighted using acres harvested to obtain the monthly average temperature and total precipitation for a given region. A piecewise linear trend is used to model the technology trend.

In the U.S.S.R. there are 31 winter and spring weather regression models covering 33 crop regions. These models cover a wide range of climate found in the U.S.S.R. whose wheat growing region spans over a thousand miles from north to south. Covering the 33 crop regions of figure 12 are 15 winter wheat and 16 spring wheat yield models. Winter wheat is grown primarily in European U.S.S.R. Since 1949, both spring and winter wheat have shown an upward yield trend. Factors contributing to improved yields include improved varieties, increased mechanization, greater fertilizer use, increased irrigation and applications of pesticides. Winterkill and moisture stress are two major weather hazards that reduce both harvested acreage and harvest yields.

3.3 PHASE I SYSTEMS PERFORMANCE

In Phase I, the experiment was successful in piecing together from existing hardware and technology a system capable of processing the required volume of Landsat data. Approximately 2604 acquisitions from 693 segments were analyzed. A total of 411 of these segments form a selected sample population representing the Great Plains yardstick region.

During Phase I, an average of about 12 hours of analyst "contact" time was required for analysis to derive a wheat proportion estimate for a 5- by 6-mile sample segment. In the experimental 1-shift-per-day, 5-day environment, an average of 30 days was required to move a segment from its moment of acquisition by Landsat through to a final wheat proportion estimate. In an operational environment, the required time could be reduced to less than 15 days.

Significant experience was acquired during Phase I in the analysis of Landsat data to estimate wheat acreage. A portion of that experience was gained locating and eliminating system and analysis problems. One analysis problem dramatically affected the early season LACIE acreage estimates until it was located during the latter half of Phase I. Bare soil was correctly classified as such but was erroneously aggregated as wheat acreage in early estimates. This led to high overestimates of wheat acreages in both the spring and winter wheat area reports until early acquisitions were replaced by later season data. Near the end of Phase I, this and other less significant problems were corrected, and a final analysis of all the Landsat acquisitions was completed with the result that the at-harvest estimates marginally satisfied the 90/90 criterion.

As a result of an evaluation of the Phase I experience, significant changes were made for Phase II.

a. A requirement was instituted to have the complete analysis of a segment conducted by a single analyst or analyst team as opposed to having a series of different analysts individually perform the image analysis, the machine processing and the evaluation functions required to develop and check a proportion estimate for a 5- by 6-mile sample segment. The team approach afforded analysts an opportunity to develop an understanding of the interactions of the various analysis procedures, thus leading to a more accurate final estimate.

b. Every cloud-free acquisition of each sample segment was to be analyzed as opposed to utilizing one acquisition in each of four different biowindows. This change was required because of the uncertainty of estimating the biowindow of wheat at a specific time as well as a lack of understanding of the best times to differentiate wheat from other confusion vegetation.

c. Modifications to the sample strategy were made to compensate for a larger-than-desired sample error detected by accuracy assessment analyses. Full frame Landsat imagery was used to refine the sample frame by deleting segments with no agriculture and reallocating them. In North Dakota where sample error was deemed excessive, 20 additional segments were allocated for Phase II.

d. Blind site ground truth proved to be an invaluable aid in problem diagnosis during Phase I. In Phase II, the Phase I blind site complement of 20 segments was increased to 140. Each blind site is visited twice a year by personnel of the USDA Agricultural Stabilization and Conservation Service (ASCS) and the identity of each field is established.

3.4 PHASE II

In Phase II, 9276 acquisitions over 1720 segments were collected and analyzed. The system was augmented with a computer parallel processor to support the increased processing loads. In addition, the average contact time required for the manual portion of the analysis of a sample segment was reduced from 12 hours of Phase I to 6 hours, as a result of more efficient analysis procedures.

In order to handle the increased data load, incurred by examining each acquisition, an additional type of analysis routine was used. A "no change" analysis routine required an analyst to overlay a computer classification map from a previous acquisition over a color-infrared image created from the new acquisition and manually determine if a change of more than 2.5 percent in wheat acreage had taken place. Given such a change, the segment would be reprocessed. The average time required for this was approximately 1 hour. As a result of inadequate amount of wheat training data in low-acreage segments, a third type of routine required an analyst to manually interpret a color-infrared image made from the Landsat multispectral data and handcount wheat pixels where less than five percent of the sample segment was in wheat. The average time for this type of analysis was approximately 2½ hours.

In Phase II, the LACIE system was successful in acquiring and processing the meteorological data from the WMO stations through the yield and crop growth models programmed on digital computers. Thirty-day average values of precipitation and temperature were utilized in the yield models in Phase II. Daily maximum and minimum temperatures were collected as inputs for the wheat growth-stage model.

LACIE experimenters were particularly interested in the repeatability of Phase I at-harvest results in the Phase II crop year. Also, the question of how early and how accurate wheat production estimates could be made prior to near harvest was of primary interest. In addition, critical attention was placed on an evaluation of how well the yield models would perform in foreign regions where historic data was thought to be of much poorer quality than that of the United States. Also in question was an issue of how well the models might perform under abnormal weather conditions that might occur in some part of the United States, Canada, or the U.S.S.R. The 1976 crop year did provide a departure from normal weather patterns in the U.S. Great Plains yardstick region. Except for the months of November 1975 and April 1976 the crop year was very dry. It should also be noted that much of the above-average November precipitation occurred at a time when the crop was entering dormancy.

Because of the severity of the drought conditions during Phase II, LACIE established an Episodal Events Team (EET) to monitor the development and intensification of the drought in selected U.S. regions that were initially identified by the use of meteorological data.

The objectives of monitoring the drought episodal event were: (1) to determine the extent of the 1975-1976 drought in the selected regions, (2) to determine the effects of this drought upon acreage, yield, and production of wheat, and (3) to develop procedures for monitoring drought using remote-sensing-based criteria. The data developed by the EET investigation were not to be used directly in Phase II analysis and production estimates.

The technical approach of the EET involved the use of Landsat images of 5 x 6 n.mi. LACIE sample segments, and full-frame (100 x 100 n.mi.) imagery at 9-day intervals to identify the drought area and quantify the effects on the wheat acreage. Yield model simulations were run to extrapolate the effects of the drought on yield estimates at harvest, assuming 10 and 90 percent of normal rainfall for subsequent months and 30-day forecast. A survey of Landsat data for improvement of distribution of rainfall patterns in the drought area was done for April and yield models were run for drought-affected crop reporting districts (CRDs). Since the data was not operated in Phase II estimate operations, special aggregations using EET data were performed for the drought area CRDs by the LACIE Crop Assessment Subsystem to evaluate the utility of remote sensing for monitoring the effect of the drought on wheat area, yield and production [6, 7].

3.5 ACCURACY OF SURVEY ESTIMATES

Results of LACIE to date are particularly encouraging in the winter wheat regions of the world where, in Phase I and II, the LACIE survey estimates have greatly exceeded expectations. The LACIE technology has produced encouraging early and excellent mid-season estimates. In addition, the winter wheat estimates at harvest were more than adequate to support the 90/90 criterion. In fact, for the U.S. winter wheat yardstick region, the 90/90 criterion was exceeded for the May 7 and later estimates (fig. 13). The May estimates were based on Landsat data acquired through the first week in April (fig. 14). Therefore, an operational system with a 14-day turnaround could have produced quite an accurate estimate in mid-April, some 2½ months prior to harvest.

In the U.S.S.R. winter wheat indicator region (fig. 15), all indications point to survey estimate accuracies comparable to those in the United States. While the excellent yardstick estimates are not available* for comparison at the U.S.S.R. indicator region level, the computed confidence of the LACIE acreage survey estimates indicate accuracies supportive of the 90/90 criterion.

Only one significant problem has been encountered in the winter wheat survey regions. During Phase II, Oklahoma and other states of the southern Great Plains, experienced generally dry conditions through April 1976. These conditions created poor wheat stands and subsequent acreage underestimates. In some cases, sparsely vegetated fields were not detected as "emerged" acreage in the Landsat or even the aircraft-ground-truth color-infrared imagery. The April rains greatly improved the wheat stands. However, the drought-altered growth cycle misled the analysts in late season to believe the late-recovering wheat to be a spring-planted crop. The tendency to underestimate wheat area in Oklahoma was not observed in Phase I, LACIE estimates being to within 3 percent of the SRS. Episodal events such as the drought-altered growth cycle in Oklahoma just described are a part of the learning process. As more of these situations are encountered, the technology will adapt to accurately estimate their impact on acreage, yield, and production. Phase III will see a greatly enhanced episode monitoring effort.

The results of 2 years in the U.S. northern Great Plains and one year in Canada (figs. 16, 17), indicate a greater tendency to underestimate spring wheat acreage than is seen for winter wheat. However, this tendency is not observed in the U.S.S.R.** for either spring (fig. 18) or winter wheat. As was identified at the end of LACIE Phase I, some spring small grains cannot yet be reliably differentiated from spring wheat using Landsat data alone. Spectrally these crops are similar, as are their growth cycles. Therefore, until procedures could be developed and tested in Phase II for use in Phase III to improve discriminability of these crops, historic ratios of these acreages were used to reduce the Landsat estimates of total small grains to an estimate of wheat acreage. The use of these historic ratios introduced additional error into the spring wheat acreage estimates, particularly in the Phase II crop year for which the planting of wheat in preference to non-wheat small grains had greatly increased from previous years. In many instances, the current ratios were as much as 60 percent greater than the historic ones used in LACIE. This was responsible for a significant amount of the underestimates of wheat acreage in Canada. There is, however, in addition to the ratio factor, a residual tendency to underestimate spring small grains acreage in the United States and Canada. This is verified by the comparisons of the Landsat estimates to ground-observed small grains acreage in the LACIE blind sites. The increased underestimation of the spring grains acreage over the winter grains acreage is thought to be partially a result of the greatly increased tendency toward strip-fallow practice in the spring wheat regions. Strip-fallow fields, small compared to

*The FAS estimates shown in figure 15 are derived from country level estimates, assuming a fixed acreage ratio between the country and indicator region level - Analysis of these ratios for the past 17 years indicates a year-to-year variation in this ratio of about 5 percent. The differences noted in figure 15 are statistically non-significant.

**The FAS estimates shown in figure 18 are derived from country level estimates, assuming a fixed ratio between the country and Indicator region level - Analysis of these ratios for the past 17 years indicates a year-to-year variation in this ratio of about 45 percent.

the Landsat resolution, are difficult to detect and measure in the Landsat imagery. The absence of the U.S.S.R. spring wheat acreage underestimation problem may be indicative of more stable year-to-year ratios of spring wheat to other small grains ratios (resulting from more stringent governmental controls) and a decrease in strip-fallow practice.

An additional dimension to the accuracy of the LACIE survey estimates is the period in the growth stage of wheat when the Landsat data is acquired. Generally, three distinct regimes emerge in this regard: (1) An *early season regime* when a majority of the Landsat data used in acreage estimation was acquired in the emergence-to-jointing period of wheat development, (LACIE Biowindow 1), (2) a *mid-season regime*, when a majority of the data was acquired in the jointing-to-mature (green-to-senescence) period of wheat development, (LACIE Biowindows 2 and 3), and (3) an *at-harvest regime* when most of the data has been acquired through harvest (Biowindow 4). These periods are indicated on the abscissa of figure 13 and figures 15 - 18. Note that for each country, the acreage estimates steadily increase through the growing season. In the case of U.S. southern Great Plains winter wheat, the *early-season* acreage estimates are substantially below the final estimates. In fact, they are about as much below the final estimate as the initial SRS acreage estimates (dashed line) are above it. The *mid-season* estimates increase substantially and are not significantly different than the final estimates. The *at-harvest* estimates increase just slightly and are somewhat more accurate, i.e., more in agreement with SRS/FAS estimates, than the midseason ones.

An analysis of ground truth and other data shows that this phenomenon is purely physical in nature and not merely a statistical artifact. In the *early-season* reports, when a majority of the Landsat data is acquired in Biowindow 1, the wheat plant sizes vary from about an inch to over a foot in height with percentages of field area in vegetative ground cover varying from almost none to somewhat less than 40 percent. Observations from ground truth indicate that fields with less than 20-percent vegetative ground cover do not provide a sufficiently "pink" response on color-infrared Landsat imagery. That is, sparsely vegetated fields are not discernable as vegetation by the analyst. Since the analyst procedures call for the identification of detectible wheat (as opposed to an estimate of wheat planted) these *early-season* estimates are low, a result of incomplete emergence of all wheat.

By *mid-season*, the wheat has completely emerged and the LACIE acreage estimates agree quite well with ground truth.

Regarding the performance of the first-generation yield models employed in LACIE, 2 years experience with the models and tests of them over 10 years of historic data indicate adequate performance in estimating wheat yields at the national levels of those countries for which adequate historic and current meteorological data are available. At levels below the national level, investigations have shown a need to improve the LACIE yield model's response to extreme weather conditions. In South Dakota for example, 1975-1976 was an extremely dry year with wheat yields estimated by SRS to be only eight bushels per acre. The South Dakota yield model estimated 17 bushels per acre and would have estimated 13 bushels per acre even if zero values for precipitation had been entered into the model throughout the year. The tendency to perform unrealistically in extreme conditions is common to overly simple crop-yield-model forms which do not adequately reflect the response of the plant to its environment. A second generation approach to yield modeling is being evaluated for selected regions in Phase III. The second generation models employ improvements such as a versatile soil moisture budget (as opposed to precipitation input alone), response to moisture and temperature tied to actual development state and use of daily (as opposed to monthly) weather variables. In spite of the difficulties inherent with the first generation models, they have served LACIE well. In fact, from figure 13, it can be seen that the LACIE yields were variable from month to month. They reflected the early dry season by a reduction in the yields followed by a corresponding increase through harvest.

3.6 PHASE III TECHNOLOGY MODIFICATIONS

As discussed in earlier paragraphs of this section, substantial improvements in remote sensing crop surveys can be expected in the future. For Phase III, the highest priority lies with technology improvements for identifying spring wheat directly from the Landsat data. Procedures, utilizing improved analyst aids such as interpretation keys and displays of quantitative spectral data are being developed. In addition, econometric models for the prediction of wheat-to-small-grains ratios will be developed and tested in Phase III. These models will predict the current ratios of wheat to small grains resulting from influential factors such as historical crop and livestock patterns, current year growing conditions (available soil moisture, etc.), economic conditions, and prevailing government farm programs. In Phase III and the transition years beyond, LACIE will implement improved partitioning of the survey region into subregions which are climatologically and agriculturally homogeneous. Such partitioning will render sampling strategies more efficient and thus more cost-effective. In addition, the ag-climate data compiled to effect partitioning will improve the project's understanding of the ag-climate properties of the survey regions and thus improve the ability to correctly classify crop acreage and estimate yield.

In Phase III, LACIE will implement greatly improved classification procedures; improvements based on our extensive experience in the initial phases of the experiment. These procedures will be much less labor intensive than the first generation ones and should, in addition, provide the analyst with improved and more repeatable decision-making procedures. The spectral differences between wheat and non-wheat, small grains and non-small grains as observable on multiple Landsat acquisitions have proven invaluable to LACIE analysts to manually identify wheat or small grains in order to train the classifier. However, because of technical difficulties, not much use was made of multi-temporal spectral data in the machine-processed estimates during Phase II. A revamped analysis approach developed over an 18-month interval is being implemented in Phase III. The approach, based on the experience and learning of researchers in LACIE through Phase I and II, is designed to be more automated and to take advantage of the multi-temporal differences known to exist in Landsat data. Analyst "contact" time for segment analysis has been steadily declining from about 12 hours in Phase I, to 6 hours in Phase II and a projected 3 hours in Phase III with the new procedures, an efficiency increase of a factor of 4 from Phase I. Landsat C, to be launched in the near future, will have improved spectral range and spatial resolution in comparison to Landsat 2. This should significantly improve classification and acreage estimation accuracies. Improved yield models will also be implemented in Phase III. These models include agronomic variables not now included but which are known to affect yield. In addition, the importance of these variables will be made a function of crop growth stage to reflect the changing importance of these different variables throughout the growing season. LACIE will also be monitoring episodic events more intensely to assess their impact on yield. Phase III will also include an evaluation of a second-generation sample strategy. In addition, the first-generation strategy is being modified for Phase III. Two hundred U.S. segments have been added to the 400 existing Phase II segments. The Landsat full-frame data acquired in LACIE was also utilized to improve the sample frame by deleting segments which fell into areas with no agriculture and randomly reallocating them to agricultural areas. Over 700 such segments were relocated in the U.S.S.R. The first generation sampling strategy is a stratified random strategy where the strata and sample allocations are based on historic data only. These strata are necessarily confined to political reporting boundaries. The second-generation approach utilizes Landsat full-frame imagery, along with climatological and soil information to develop the strata and to determine the optimal segment allocations to the strata. Such an approach was known from the outset of LACIE to be an improvement over the use of historic data, particularly in countries whose historic data is sparse. However, this approach was not possible to implement until only very recently because of the unavailability of Landsat imagery over foreign countries and the lack of techniques for discerning small grains on the imagery. A year and one-half of data collection by Landsat and a similar amount of image analysis experience in LACIE now makes implementation of such techniques possible.

4. A LOOK TO THE FUTURE

As currently envisioned, LACIE is a major step toward developing a remote sensing survey technology capable of global food and fiber monitoring. The contribution of LACIE will be a demonstration of "proof of concept" of this new technology for significantly improving currently available information on one major global crop - wheat. By the end of LACIE Phase III, it is anticipated that the experiment will have demonstrated the utility of remote-sensing-survey technology over several countries, will have identified key areas where the technology needs improvement and will have brought the USDA advanced system to a point of initial testing. At this time, a transition period will be required to complete, document and transfer the LACIE technology to an evolving USDA system to exploit the experimental accomplishments of LACIE. In this overall development, demonstration, and application program, focused on a global food and fiber monitoring system, the next logical steps are (1) the continuing refinement of the technology, and subsequent transfer of both skills and technology to an operational test system within USDA, and (2) the adaption of the LACIE technology to multi-crop food and fiber inventory applications.

Early in LACIE Phase II, an effort was initiated to accomplish the transfer of technology to the USDA for further evaluation. This effort is now an approved follow-on to LACIE and is officially designated, LACIE Transition. The objective of LACIE Transition is the orderly transfer of proven technology to USDA facilities and personnel. In LACIE Transition, USDA will construct and operationally test a first-generation global information system capable of producing timely, reliable, and objective estimates of the global wheat supply. LACIE Transition will begin with the start of the 1977-1978 crop year and will conclude in 1981. As USDA begins an orderly, country-by-country expansion of their operational test system through 1981, the experimental system will be utilized to refine the wheat-inventory technology in important wheat producing regions and to validate the technology prior to transfer to the USDA.

In addition to the transition efforts, the technology developed in LACIE will be adapted to inventory production of other food and fiber crops. These include corn, rice, soybeans and non-food crops such as forest and timber inventories. It will also be adapted to monitor forage conditions within the world's important rangeland. This increased capability could conceivably be developed and incorporated in the mid-to-late 1980's in a second-generation global food and fiber monitoring system.

The goals of LACIE, LACIE Transition, and the technology expansion to a multi-crop application will continue to require a strong supporting research and technology development effort within the research community. In this regard, LACIE can be considered as a paradigm for the multi-crop application. That is, estimation of production for other crops will involve estimation of the same fundamental elements involved in wheat production estimation: crop area, average plant or producing unit population per unit area and average productivity per producing unit. It should be emphasized that the estimation approach utilized to date in LACIE is not the only approach which can be taken to estimating these quantities and quite possibly modifications of the LACIE approach will produce more an optimum survey approach for applications different than global wheat estimation. However, all such approaches will involve to a large extent the same data input and analysis systems required for LACIE, as well as many of the same solutions to technology problems.

To be more specific, the LACIE approach to date has utilized primarily Landsat data to estimate wheat acres for harvest and primarily meteorological data to estimate the average productivity, or yield, for each acre harvested. In a sense, this separation is artificial. As is pointed out in the Landsat spectral displays of figures 5 through 7, there is much information in the spectral data relating not only to total acreage but also to the plant population density within the acreage. There is, in addition, information relating to plant condition and, thus, average yield. Plant characteristics which can be measured well in advance of harvest are known to be correlated with final yield as well as the environment of the plant. Therefore, a model which includes the effects on yield of not only the plant's environment but also its physical characteristics (height and stand density) from which early yield estimates based on soil moisture may be

made [11] will be a significant improvement over models utilizing only meteorological data. Potential quantitative connections through modeling, involve efforts which relate leaf area index to evapotranspiration [12], leaf area duration to yield and leaf area index to Landsat spectral response [13]. With the advent of thermal sensing on Landsat C, additional information will be available which is a potential predictor variable for crop yields [14].

Conversely, meteorological data also contains much information relevant not only to average productivity but also to planted and harvested acreage. For example, the LACIE early season estimates of emerged acreage are a fraction both of the total planted and that expected to be harvested. This fraction within a segment is related to the average growth stage within the segment which is in turn strongly related to the segment temperature and precipitation history. Therefore, in early season, the LACIE estimates of emerged acreage could be used in a regression model, involving both temperature and precipitation inputs, to predict the total acreage to emerge at a later date. The emerged detectable acreage is, of course, also related to the acreage to be harvested through meteorological and economic factors. Based on an analysis of these factors, models could be developed which relate acreage at any one point in time to that anticipated for harvest.

Considering then that meteorological and spectral data are both strongly related to total acres, plant population density, plant condition, and therefore total production, it is anticipated that the survey models utilized for LACIE will evolve toward forms which simultaneously account, in a more integral fashion, for these effects. In such a form, the production, acreage, and yield estimators would each involve predictor variables based on both spectral, meteorological, and even agronomic and economic data such as fertilizer application rates, cropping practices, and prices.

Another area for development within the near future is improved sensing and measurement of the basic predictor variables themselves. To date, LACIE has utilized first-generation earth-resources satellites along with meteorological data obtained from the WMO ground stations. With the advent of the second-generation earth-resources satellite, Landsat C, and the development of a capability to utilize environmental satellite data to obtain more complete coverage for temperature and precipitation estimates, the survey estimates should significantly improve. The LACIE analysis experience has indicated that the Landsat data itself contains information regarding temperature and moisture, as these factors are manifest in crop condition and loss of vigor resulting from drought (see figures 6 and 7). Parameters such as soil moisture or alternatively precipitation and temperature can probably be more reliably and accurately estimated from a combination of Landsat-type and meteorological satellites.

The direction for the future, then, is the development of crop-production-estimation models based on both agrometeorological and spectral data which account for the influence of these data on both acreage and productivity. In addition, these models and approach must be adapted to the other major global food and fiber crops. Improvements in survey estimates will also be derived from basic improvements of the predictor variables themselves as a second-generation land satellites become available and as the use of environmental satellite data is incorporated along with land satellite data to estimate these parameters.

The NASA, together with the USDA and the DOC, is already beginning to look ahead and to plan a technology development program required to support the future implementation of operational global food and fiber monitoring systems. A methodology to best insure a suitable technology base, together with an adequate understanding of its use, needs to be developed over the next year or two and vigorously implemented if its output is to be available for the mid-to-late 1980's.

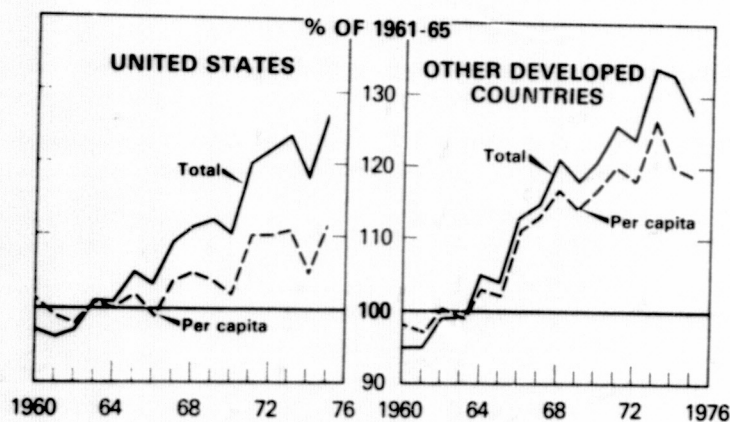
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YEAR BEGINNING JULY 1	UNITED STATES ¹	OTHER COUNTRIES	WORLD TOTAL
	1,000 metric tons	1,000 metric tons	1,000 metric tons
1964	18,107	18,343	36,450
1965	25,943	16,990	42,933
1966	21,406	21,029	42,435
1967	20,155	21,245	41,400
1968	16,423	23,579	40,002
1969	19,640	23,376	43,016
1970	19,784	26,616	46,400
1971	21,038	32,362	53,400
1972	35,812	24,688	60,500
1973	44,329	29,871	74,200
1974	34,693	33,210	67,903
1975 ²	44,864	37,767	82,631

¹ Includes corn and cornmeal for relief and the following products: cornmeal, cornstarch, oatmeal, and barley malt. ² Preliminary.

TABLE I. WORLD EXPORTS OF COARSE GRAINS, 1964-75.



* CANADA EUROPE U.S.S.R. JAPAN REPUBLIC OF SOUTH AFRICA AUSTRALIA AND NEW ZEALAND

FIGURE 2. AGRICULTURAL PRODUCTION. Total and per capita values.

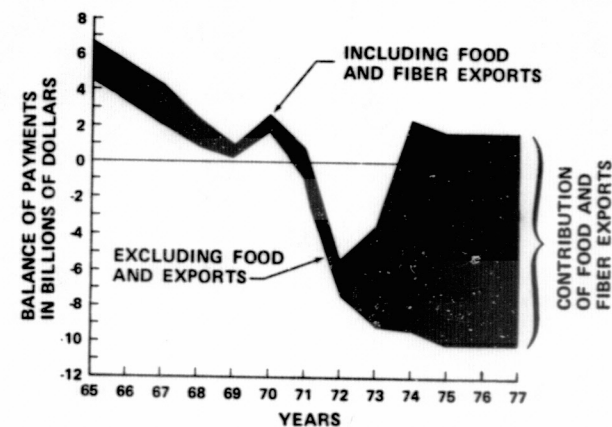


FIGURE 1. Food and Fiber Contribution to U.S. Balance of Payments.

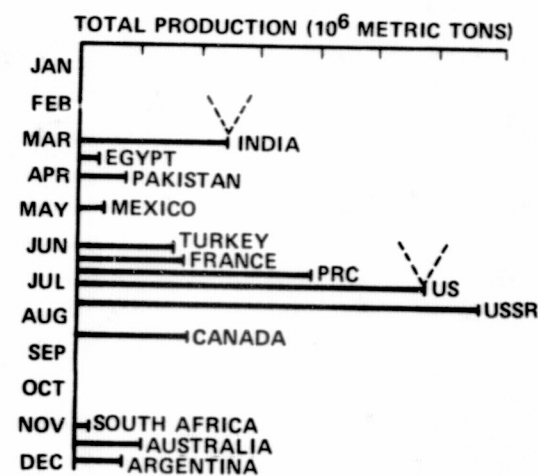
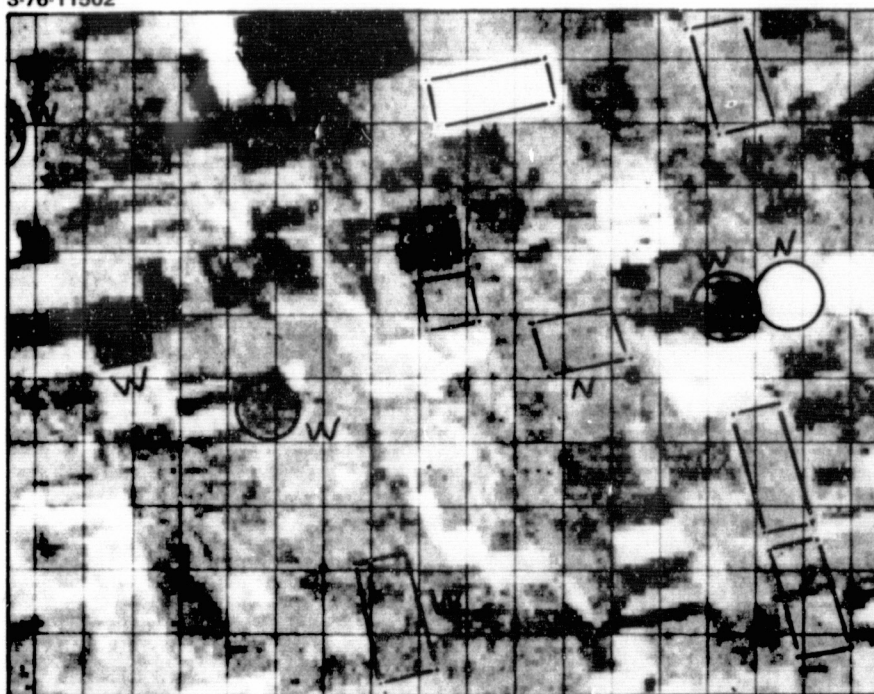


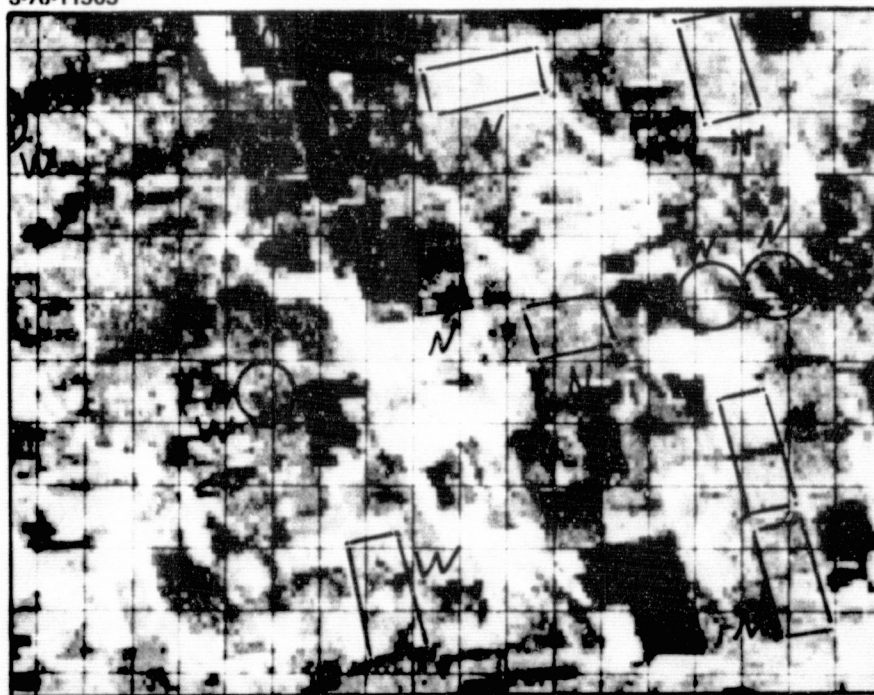
FIGURE 3. WORLDWIDE WHEAT HARVEST DATES.

S-76-11502



10 NOV. 1975 EMERGENCE

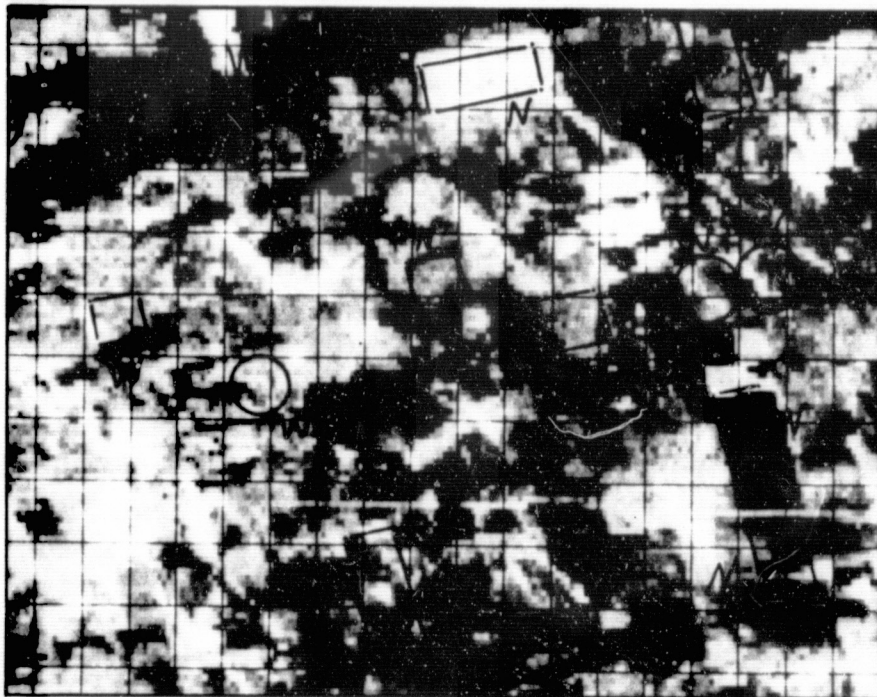
S-76-11503



25 FEB. 1976 REGROWTH

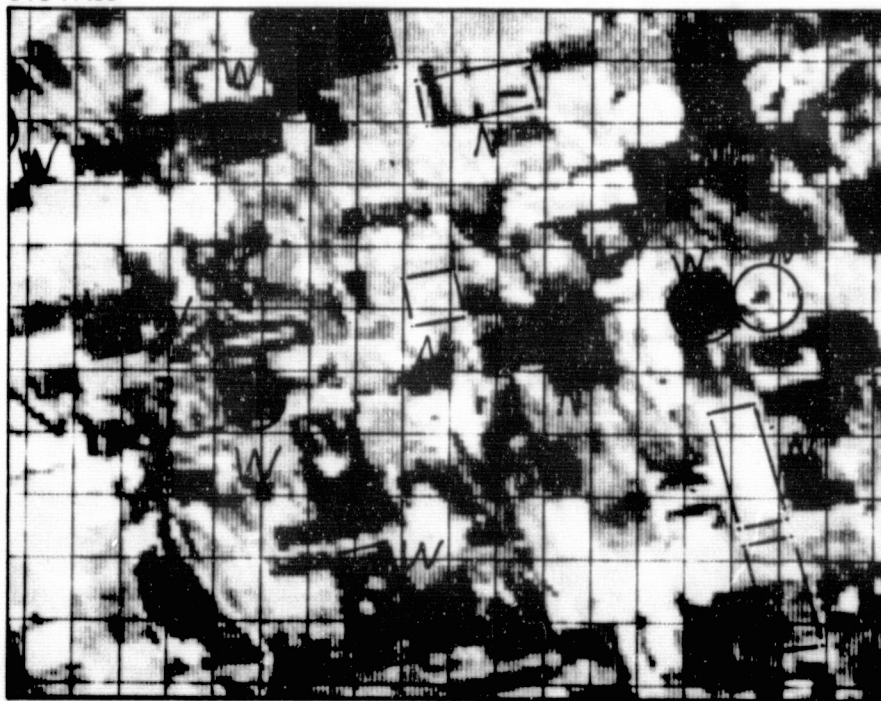
FIGURE 4a. SHERMAN COUNTY, KANSAS. Segment 1021, 1975-76 winter wheat, Landsat Computer Imagery (W-Wheat, N-Nonwheat).

S-76-11497



14 MARCH 1976 PRE-JOINTING

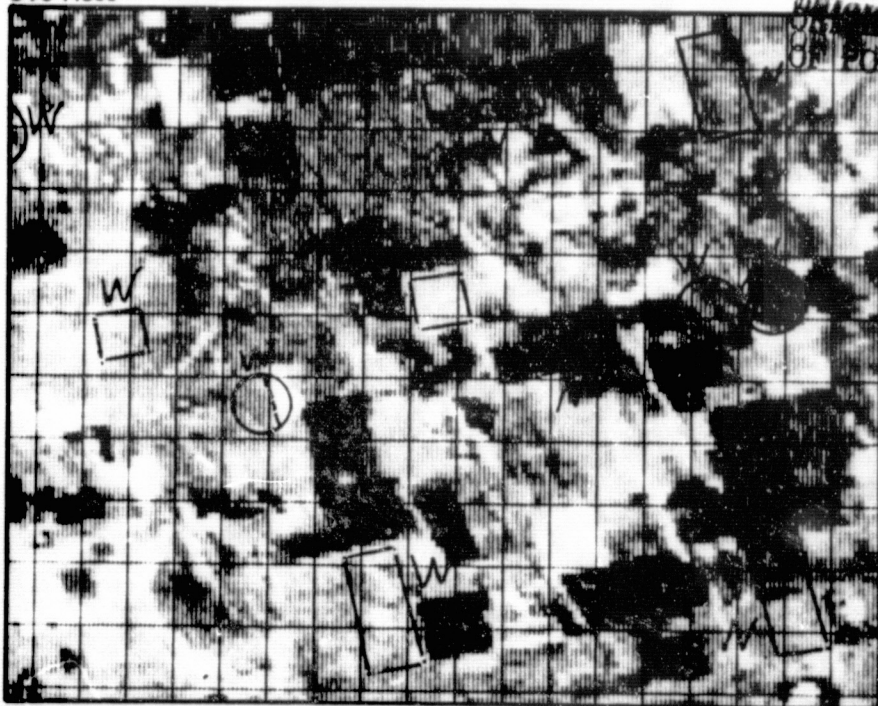
S-76-11499



12 JUNE 1976 HEADING

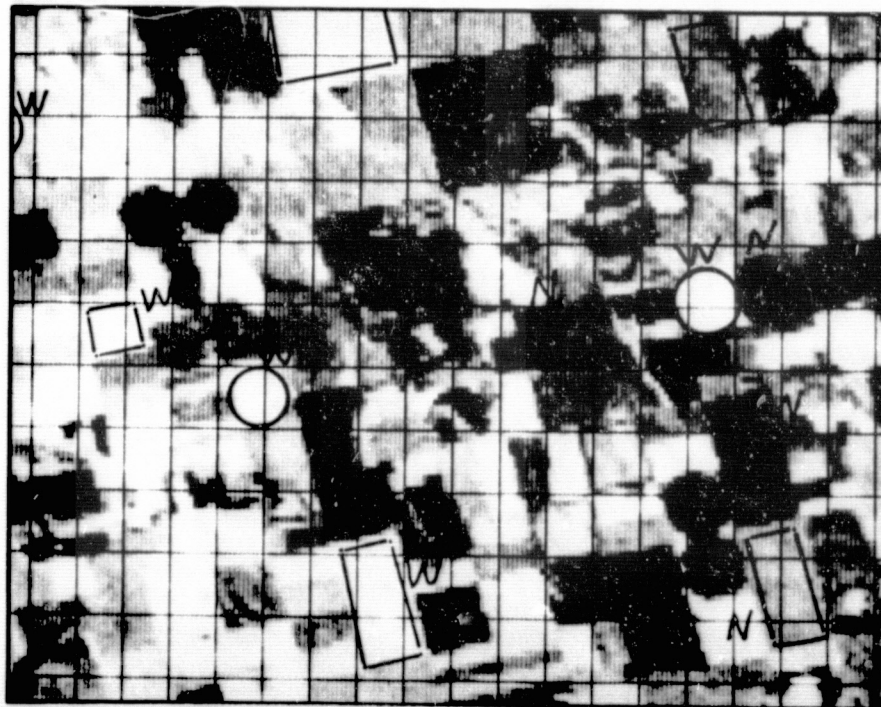
FIGURE 4b. SHERMAN COUNTY, KANSAS. Segment 1021, 1975-76 winter wheat, Landsat Computer Imagery (W-Wheat, N-Nonwheat).

S-76-11500



1 JULY 1976 SOFT DOUGH

S-76-11501



19 JULY 1976 RIPE HARVEST

FIGURE 4c. SHERMAN COUNTY, KANSAS. Segment 1021, 1975-76 winter wheat, Landsat Computer Imagery (W-Wheat, N-Nonwheat).

S-77-10845

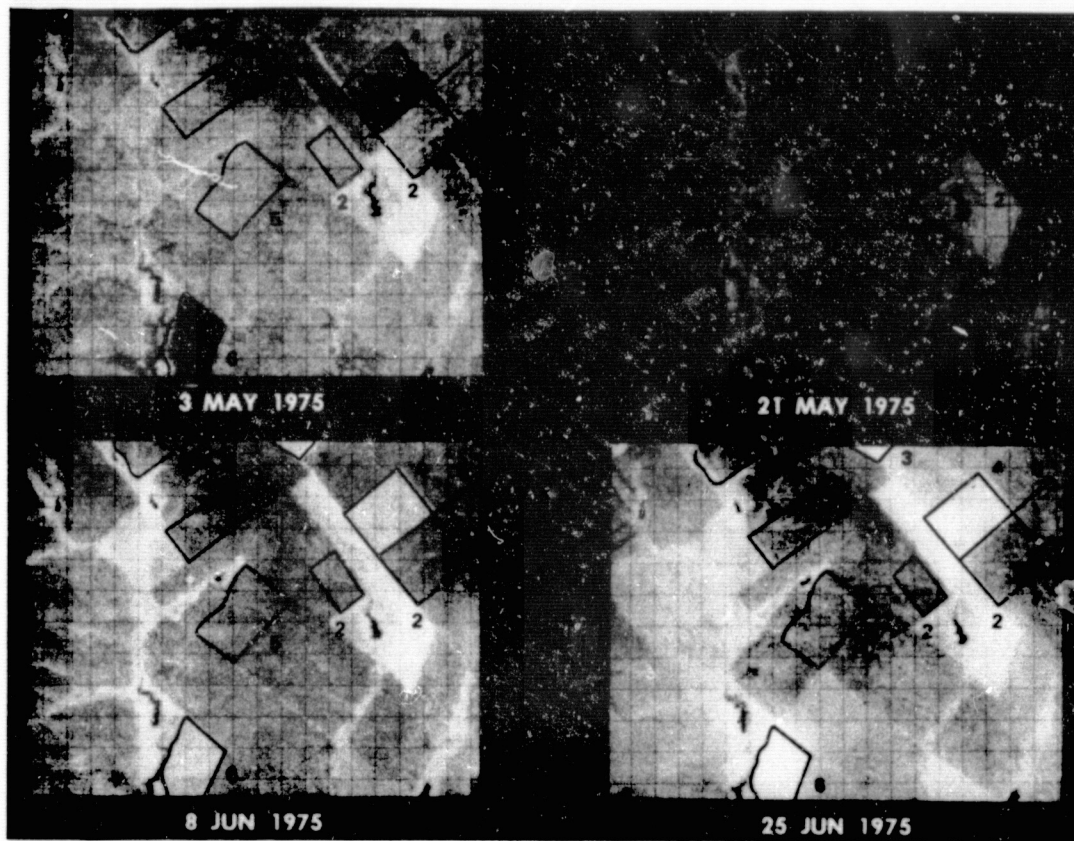


FIGURE 5a. SARATOV, U.S.S.R. Segment 7735, 1974-75 crop, Landsat Computer Imagery.

S-77-10847

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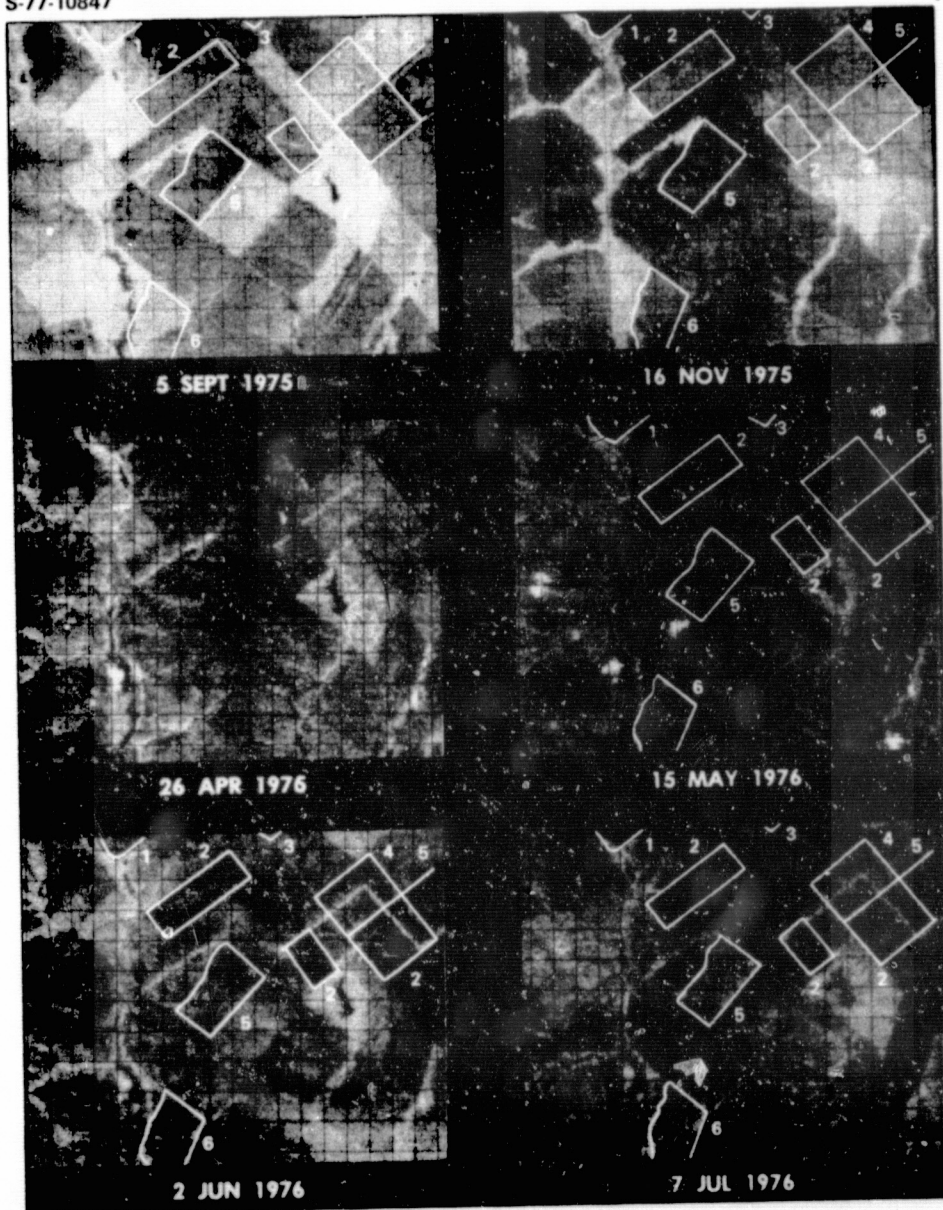
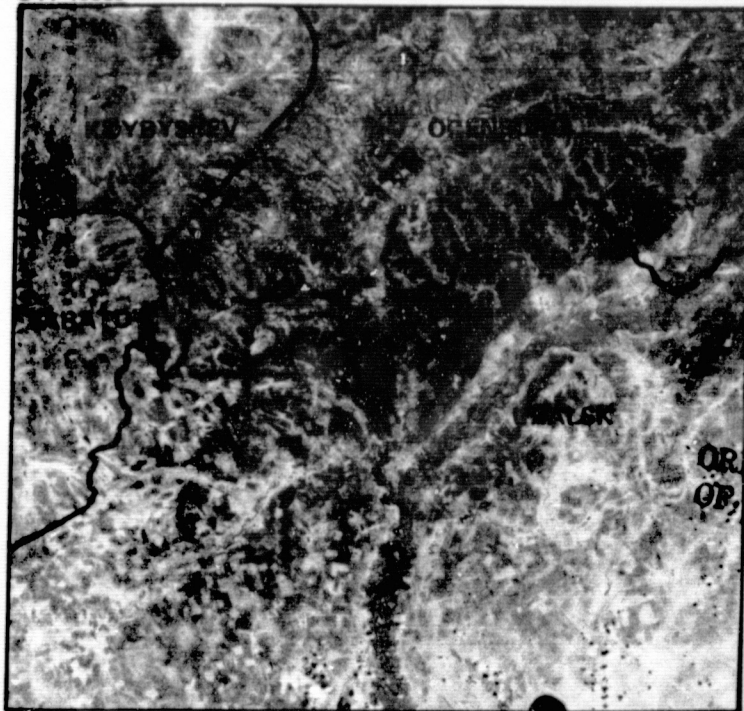


FIGURE 5b. SARATOV, U.S.S.R. Segment 7735, 1975-76 crop,
Landsat Computer Imagery.

S-77-10835



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FIGURE 6. SARATOV, U.S.S.R., REGION, 1975-76. Adequate Moisture Conditions; full frame Landsat image.

S-77-10838

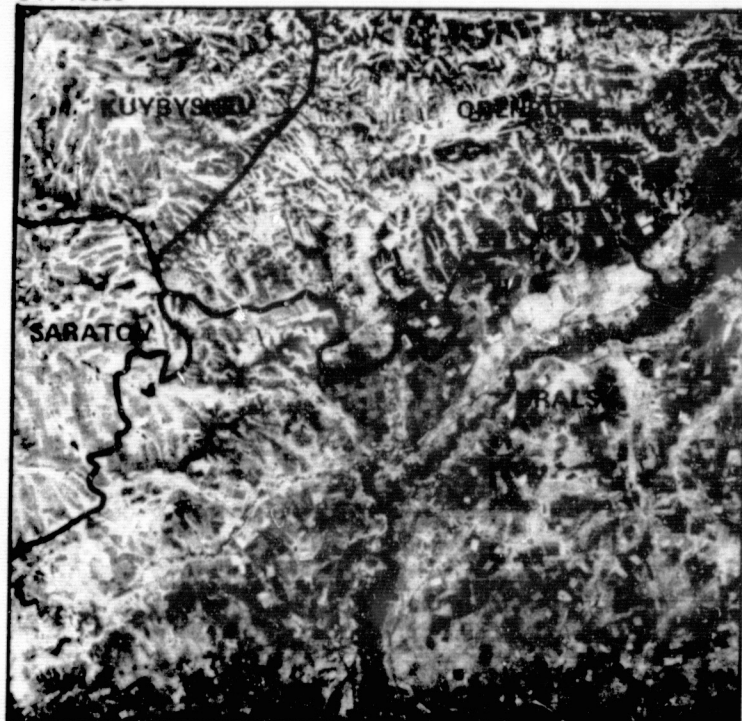
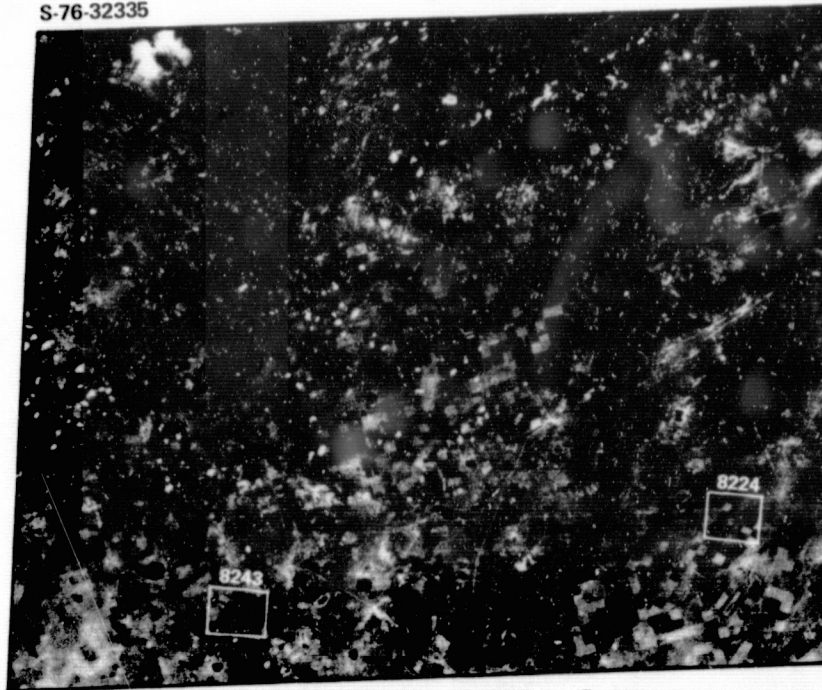


FIGURE 7. SARATOV, U.S.S.R., REGION, 1974-75. Drought Conditions; full frame Landsat image.

S-76-32335

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Full Landsat Computer Image.

FIGURE 8. KUSTANAY OBLAST, U.S.S.R., MAY 1973.

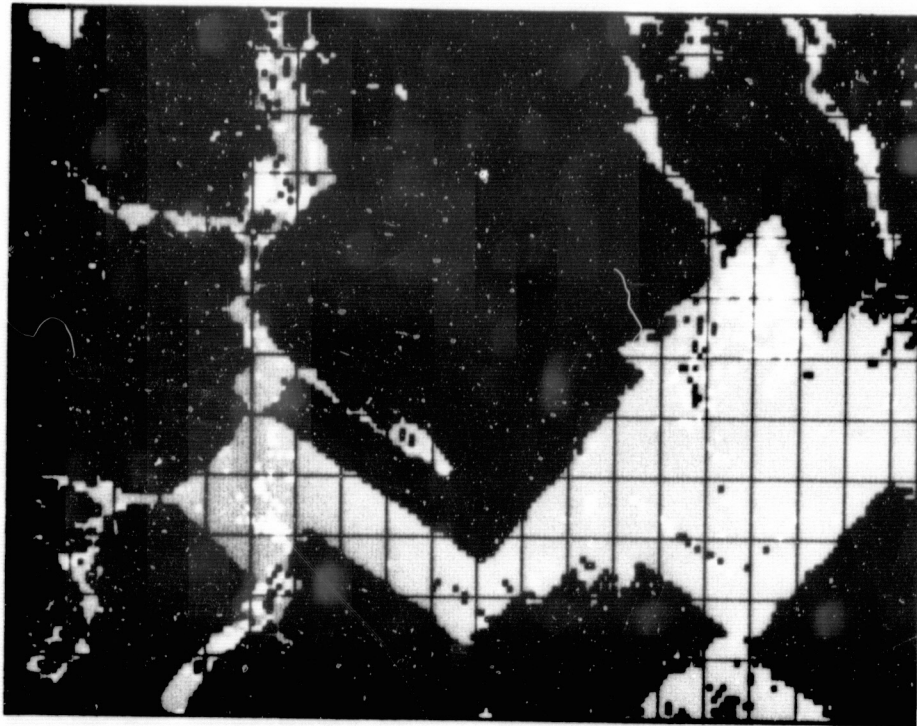
S-76-32336



Full Landsat Computer Image.

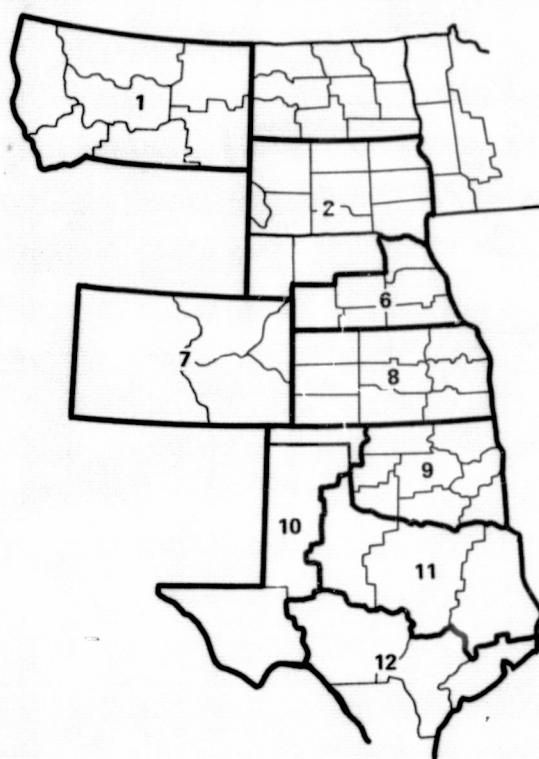
FIGURE 9. KUSTANAY OBLAST, U.S.S.R., MAY 1975.

S-77-10850

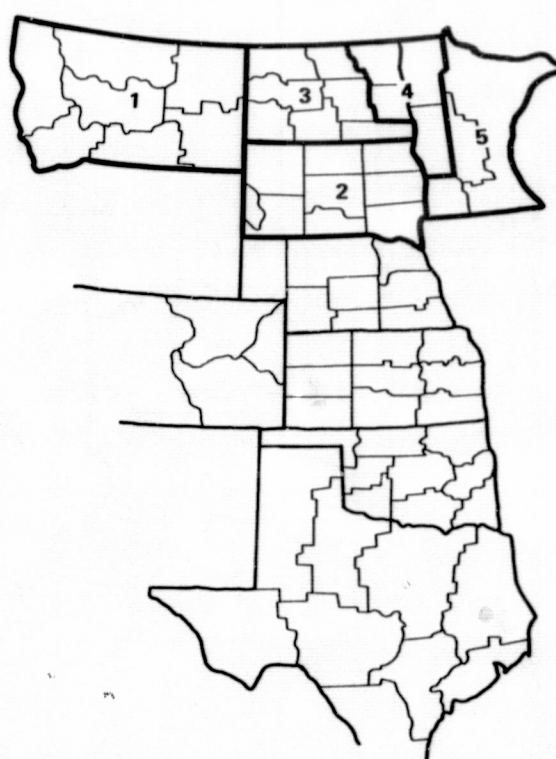


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FIGURE 10. COMPUTER-GENERATED CLASSIFICATION MAP FOR WHEAT AND NON-WHEAT. Corresponds to Landsat acquisition of 26 April 1976 over Saratov, U.S.S.R.



CCEA WINTER WHEAT MODEL BOUNDARIES



CCEA SPRING WHEAT MODEL BOUNDARIES

FIGURE 11. U.S. GREAT PLAINS WHEAT YIELD WEATHER REGRESSION
MODEL COVERAGE.

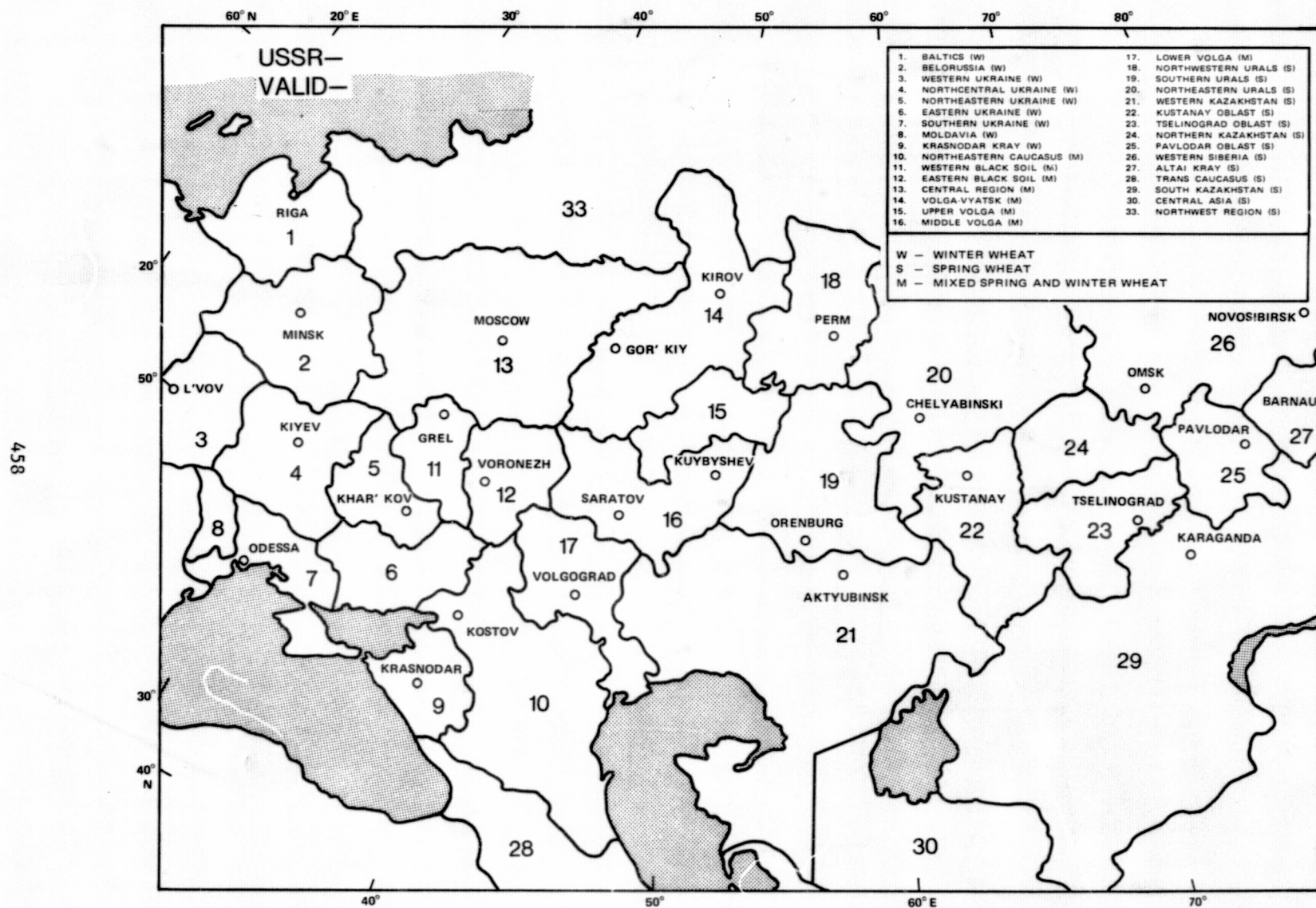
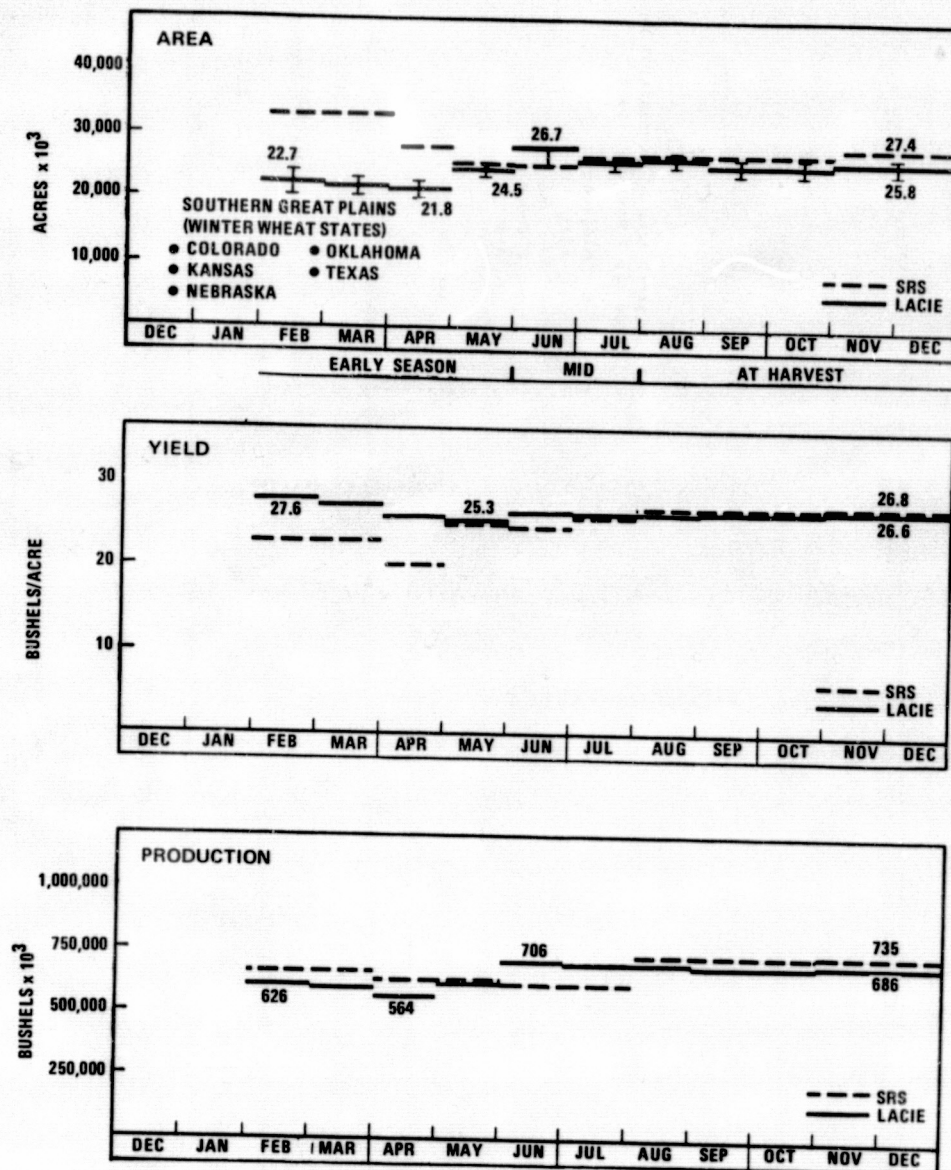


FIGURE 12. U.S.S.R. CROP REGIONS COVERED BY SPRING AND WINTER WHEAT REGRESSION MODELS. Regions 31 and 32 not shown on map.

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FIGURE 13. MONTHLY COMPARISON OF LACIE AND SRS ESTIMATES FOR THE U.S.A. SOUTHERN GREAT PLAINS, 1975-76 CROP YEAR.

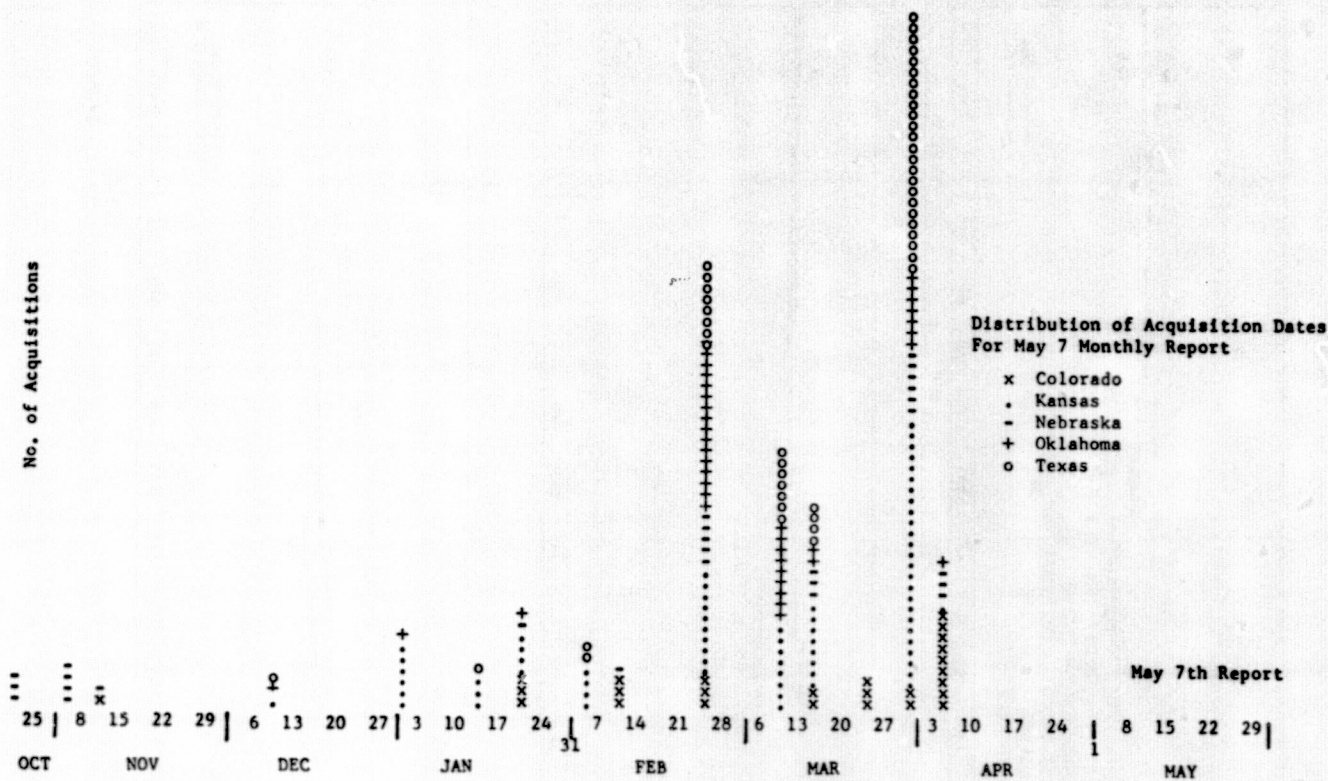
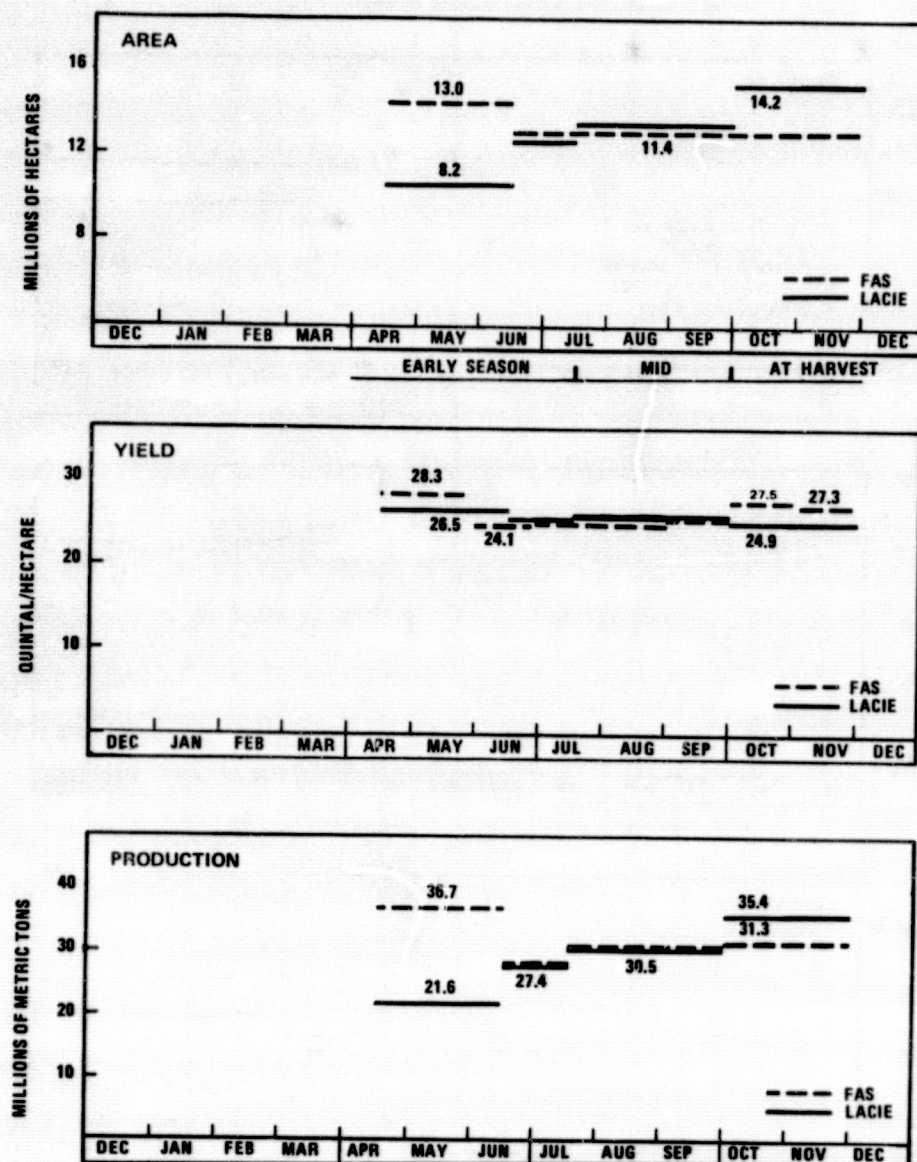


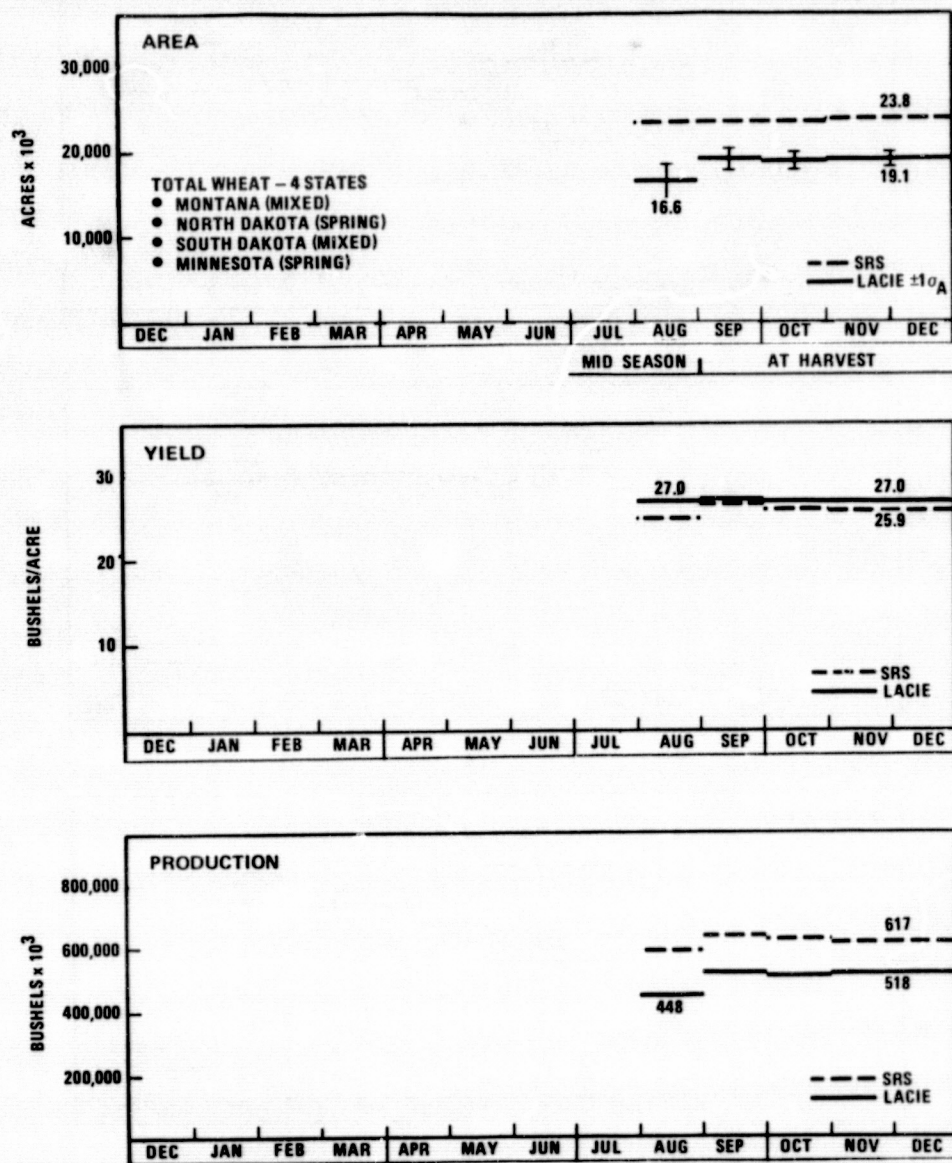
FIGURE 14. THE DISTRIBUTION OF WHEAT DATA ACQUISITION DATES. Week by week for LACIE U.S. Southern Great Plains estimates released May 7, 1976.

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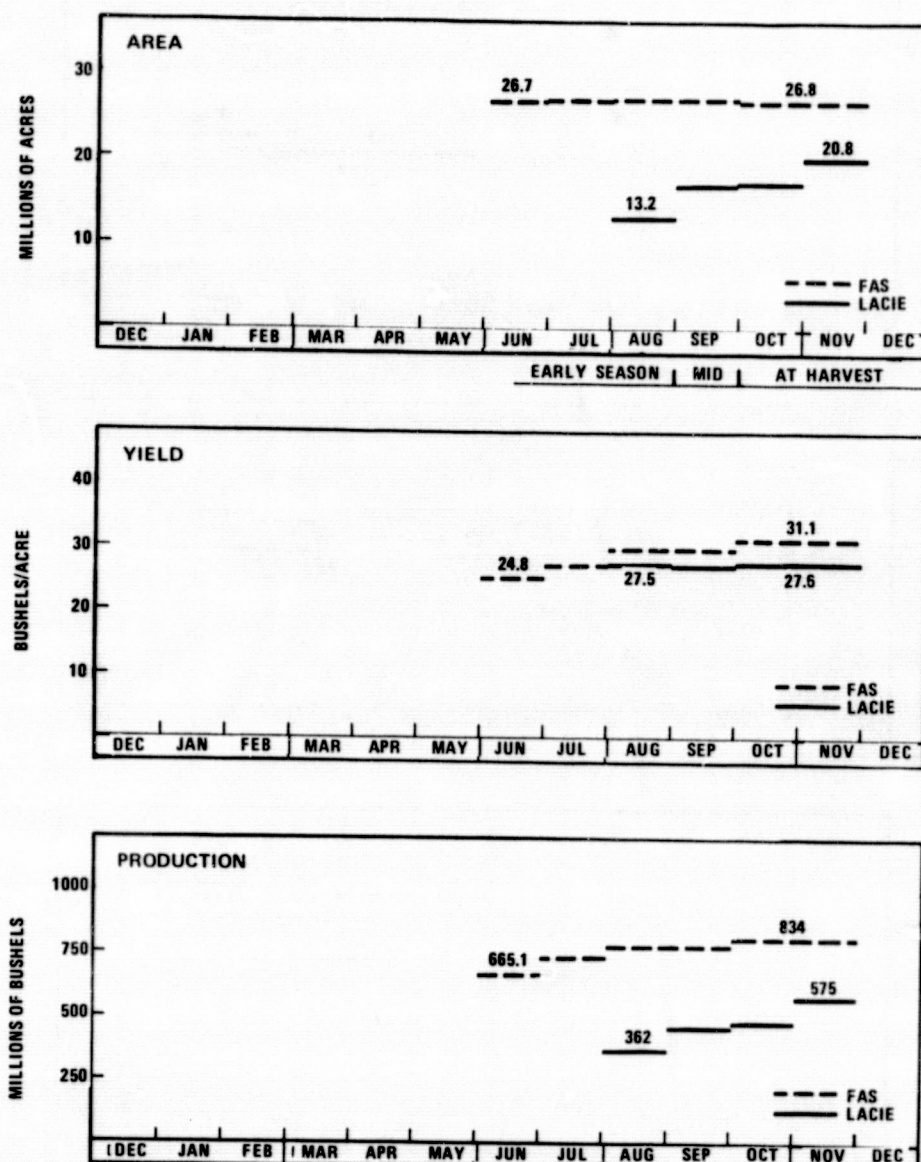
FIGURE 15. MONTHLY COMPARISONS OF LACIE AND FAS ESTIMATES FOR THE U.S.S.R. WINTER WHEAT INDICATOR REGION, 1975-76 CROP YEAR.



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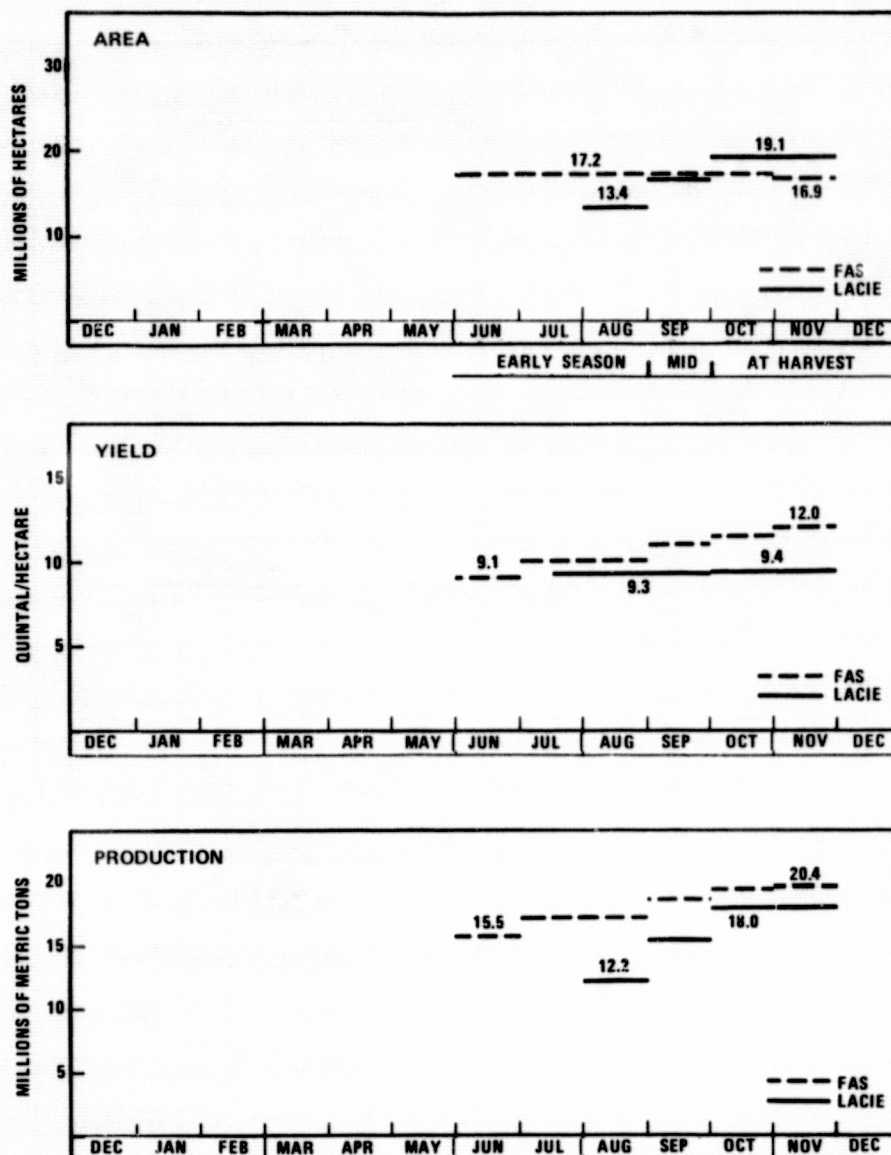
FIGURE 16. MONTHLY COMPARISON OF LACIE AND SRS ESTIMATES FOR THE U.S. NORTHERN GREAT PLAINS, 1975-76 CROP YEAR.

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FIGURE 17. MONTHLY COMPARISONS OF LACIE AND FAS ESTIMATES FOR CANADA SPRING WHEAT REGION, 1975-76 CROP YEAR.



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FIGURE 18. MONTHLY COMPARISONS OF LACIE AND FAS ESTIMATES FOR THE U.S.S.R. SPRING WHEAT INDICATOR REGION, 1975-76 CROP YEAR.

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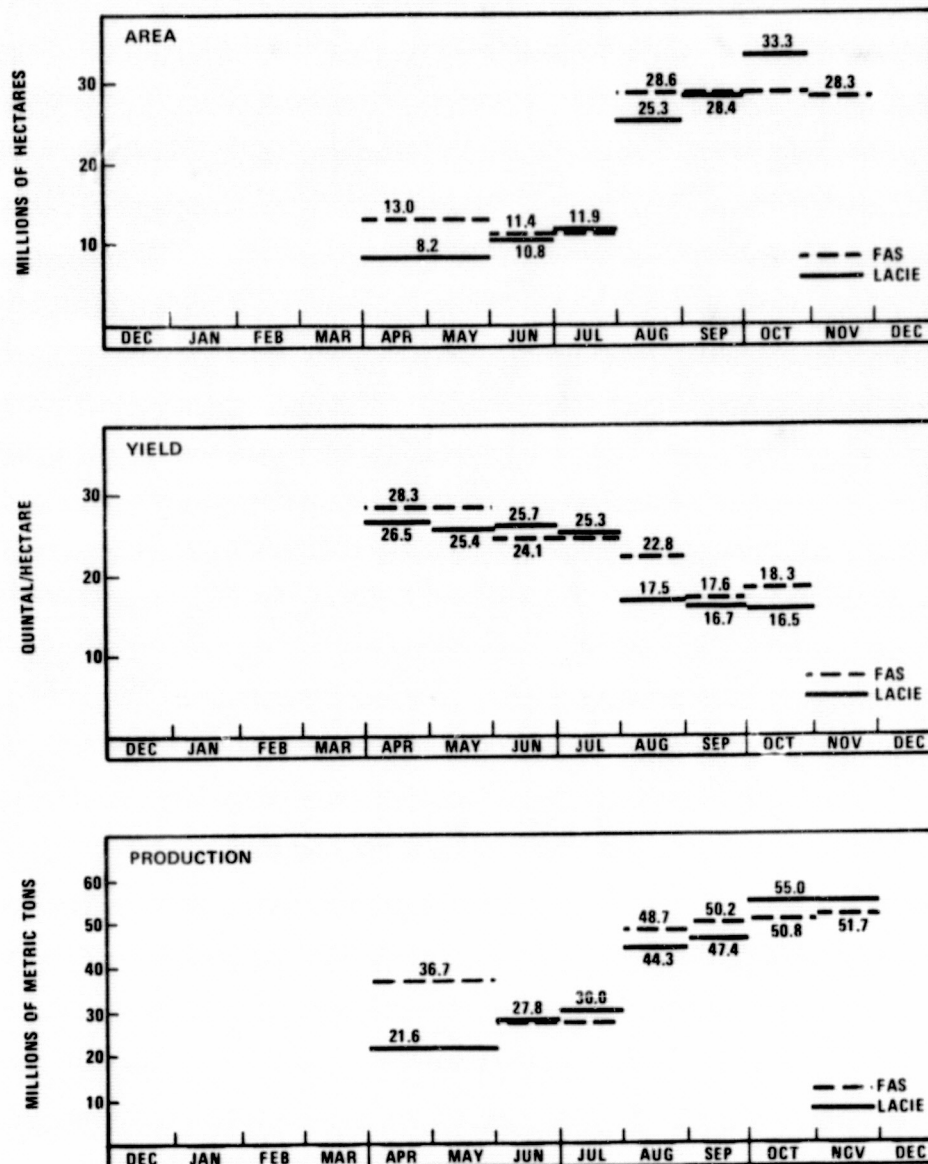


FIGURE 19. MONTHLY COMPARISON OF LACIE AND FAS ESTIMATES FOR
U.S.S.R. TOTAL WHEAT (INDICATOR REGIONS), 1975-76 CROP YEAR.

"ENERGY AND REMOTE SENSING"

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ABSTRACT

The President's National Energy Plan (NEP) and Nuclear Power Policy Statement of April 1977 constitute landmark events in national energy policy and planning. Effective implementation of these plans will require application of the best tools available. The potential contributions of remote sensing, particularly LANDSAT data, have yet to be clearly identified and exploited. These contributions, ranging from the near-obvious to the more subtle, appear to fall into the following five categories: (1) exploration by acceleration of the exploration process for naturally-occurring energy-related materials, e.g., uranium, oil, gas; (2) exploitation by improving the efficiency of extracting, processing and transporting identified mineral resources; (3) power plant siting by more effective site selection for power installations and related infrastructure through improved assessment of geological hazards (fault identification), water needs/availability, and effluents; (4) environmental assessment and monitoring through assistance in establishing environmental baselines related to energy production and in monitoring deviations, e.g., CO₂ monitoring, strip mining and land restoration; (5) transportation infrastructure by providing improved mapping and monitoring capability to ensure design and operation of most efficient (minimum energy) transportation networks principally for developing countries. The collective impact of the five categories establishes a significant relationship between the growing needs for expanded but environmentally acceptable energy production and remote sensing. A critical example is the need for a more precise estimate of the U.S. and world uranium and thorium resources as a key input into a number of crucial energy RD&D decisions. Environmental aspects of potentially greatly enhanced coal extraction and utilization represent another area for contribution. Requirements for early action on remote sensing applications to uranium resource estimation, global CO₂ monitoring and to strip mining and land restoration are emphasized.

1. THE NATIONAL ENERGY PLAN (NEP)

The most significant recent event in energy policy and planning has been the issuance of the President's National Energy Plan which includes the consequences of his Nuclear Power Policy Statement.

The nature of the U.S. Energy Problem has been characterized in the following terms: (1) our built-in energy infrastructure is based heavily on gas and oil--our most scarce energy resources--rather than on our most abundant resource, coal; (2) the prognosis for the U.S. and the world is serious unless current trends are significantly altered, and (3) action now will require minimal life style changes. Continuation of the current state of drift will make the ultimate transition to scarcity and higher prices traumatic.

The world-wide liquid hydrocarbon problem is very serious, perhaps more so than initially realized. Based upon the best available estimates, it appears that demand for OPEC oil may exceed OPEC productive capacity in the early to mid-eighties. The upward pressure on world oil prices resulting from this supply/demand gap would have serious international consequences--both financial (e.g. balance of payments) and in terms of U.S. foreign policy implementation.

In response, the National Energy Plan objectives are: (1) for the short term to reduce our vulnerability to an embargo; (2) for the mid-term to weather the peaking and decline of world oil production; and (3) for the long-term to develop renewable sources for sustained economic growth. In all time frames, the energy plan must be equitable, ensure healthy economic growth, and be kept in harmony with environmental policies.

The major strategies for achieving these objectives would be to: (1) reduce energy demand growth from the historical three percent to two percent per year by means of conservation in all sectors, reformation of the utility rate structures, and energy prices that reflect true replacement cost; (2) conversion of industry and utilities from oil and gas to coal and other abundant fuels; and (3) pursuit of a vigorous R&D program to ensure renewable resources to meet U.S. needs in the next century.

These strategies will require the following actions: (1) reduce the annual growth of U.S. energy demand to less than two percent; (2) cut in half the share of U.S. energy imported--from one-fourth to one-eighth; (3) reduce oil imports from a potential level of 16 million barrels a day to less than 6 million barrels; (4) achieve a 10 percent reduction in gasoline consumption; (5) increase coal production (currently greater than 700 million tons per year) by at least 400 million tons per year by 1985 (to some 1.1 billion tons per year); (6) insulate 90 percent of U.S. residences and commercial buildings; (7) install solar hot water and space heating in more than 2.5 million homes.

Implementation of these strategies has led to a variety of measures including the "gas guzzler" tax, the potential increased Federal tax on gasoline, and the building insulation and solar heating incentives programs.

More pertinent to remote sensing applications is how these plans and strategies have been reflected into the ERDA FY 78 energy technology budget. Table I shows the evolution from the original Ford budget to the most recent Carter/NEP budget. Large increases are apparent in the nearer term technologies of conservation, fossil energy, and solar heating and cooling, while long term technologies such as fusion, breeder, and solar electric have taken large cuts. This reflects the apparently increased emphasis by the NEP on the near and mid-term problems.

Within this structure are a number of large--and small--decisions which can have important bearing on the future of the remote sensing community. Some examples are:

First, the nuclear power policy statement, drastically restructures the breeder program, postponing indefinitely the CRBR; it defers indefinitely the commercial reprocessing and recycling of spent fuel from LWR's; it also proposes to increase U.S. production of enriched uranium fuels for domestic and foreign needs. This establishes a need for improved reliability in the estimates of uranium reserves and resources. In order to reduce the uncertainties about the domestic uranium resources, ERDA will review and recalc. its National Uranium Resources Evaluation (NURE) program to sharpen its uranium resource assessment. This will include thorium reserves and will be a cooperative effort with industry, the states, and the U.S. Geological Survey.

Second, the proposed very large increases in the production and use of coal suggest a careful study of health effects. The President has stated that he will appoint a special committee to study the health effects of increased coal production and use. The global atmospheric effects of vastly increased generation of CO₂ (greenhouse effect) would be an important consideration. Such a study effort will receive specific incremental funding in the ERDA environmental research effort.

Third, the NEP will include support for a tough, uniform strip mining law. Enforcement of the provisions of such a law will require regular, dependable, near real time information on the status of strip mining and land restoration activities.

Fourth, the Corps of Engineers has been requested to report to the President within three months on the potential for additional hydropower installations in the country.

2. REMOTE SENSING APPLICATIONS TO ENERGY

It has been apparent--even before the current intense focus on energy problems--that remote sensing from aircraft and spacecraft could make significant contributions to energy in the five ways indicated in Table II.

2.1 EXPLORATION

This involves improving the efficiency of the reconnaissance phase of exploration for energy related resources. This could have application to exploration for uranium, oil and gas, and, possibly, potential geothermal resources. There would be less contribution to coal and oil shale since the location and extent of most near-surface deposits of these two energy resources are well known in the U.S. Let us review briefly some specifics in regard to current contributions of remote sensing--especially through LANDSAT--to exploration for energy sources (references 1-7).

2.1.1 OIL AND GAS. The most immediate use of remote sensing in petroleum exploration would be producing geologic maps (rock and stratigraphic units, and structure) from images having information content in some ways superior to conventional aerial photos. This is especially valuable to exploration in undeveloped or difficult-access regions of the world. Many petroleum companies now use LANDSAT in their foreign operations to generate reconnaissance maps, search for subtle stratigraphic (facies) changes, look for unusual or diagnostic structural relations at the surface indicative of favorable subsurface conditions of oil and gas accumulation, and develop strategies for logistics access during exploration or later during the extraction phase (e.g., pipeline routing).

Soon after LANDSAT launch, there was much excitement about the possibility of detecting characteristic surface alteration postulated to result from hydrocarbons leaking from traps at depth. The so called "hazy" features described in one LANDSAT investigation report were cited as promising evidence because of a high correlation between apparent surface anomalies and underlying known petroleum fields. Subsequent examination of the evidence failed to substantiate this observation. Other studies in Wyoming, Colorado, Texas, and Oklahoma, seeking similar phenomena, have yielded only ambiguous and somewhat negative results. The issue is still in doubt but by no means closed. The prime concern is to verify that escaping hydrocarbons actually can affect the surface to produce notable alteration; until this is proved, detection by remote sensing or other methods remains a secondary consideration.

Some inconclusive but suggestive evidence that abnormally high levels of methane can be detected in the atmosphere in the vicinity of known petroleum-producing areas (and hence probably released from wellhead flares and processing plants) has been reported by N. Del Grande of Lawrence Livermore Laboratory through her analysis of Nimbus (meteorological satellite) data from infrared sensors. This type of observation must be tested over undeveloped fields to show the presence of naturally-released methane before its relevance to exploration can be established.

2.1.2 URANIUM. More promising results from LANDSAT and other remote sensing systems are emerging through applications to uranium prospecting, especially in support of the National Uranium Resources Evaluation (NURE) program. Recognition of some structural or stratigraphic controls around known deposits has been described for several localities. Uranium ores associated with sedimentary rocks are often accompanied by distinctive alteration products--chiefly hydrated iron oxides and clay minerals--subject to detection by remote sensing. Early research on the detection capabilities of LANDSAT data for use in exploration for uranium roll-type deposits indicated that single ratio techniques using LANDSAT imagery were sensitive enough to separate hematitic stain, and that a combination of LANDSAT $R_{5,4}$ and $R_{7,6}$ ratios plus a processing technique sensitive to vegetative color was recommended for detecting areas of limonite. Successful detection of such alteration at the Gas Hills (Figure 1), Crooks Gap and Pumpkin Buttes deposits in Wyoming and at Cameron in Arizona indicate the feasibility of such an approach in future exploration. Figure 1 is a band ratio image made from band 5 over band 7. However, the frequency of "false alarms" at these sites points to the continuing problem of "separating the wheat from the chaff," i.e., localizing bonafide targets from much more widespread occurrences of unrelated alteration or natural colorations in soils and rock. A sensible approach is to integrate the remote sensing observations with those from airborne gamma ray spectrometers and magnetometers to provide a three dimensional array of pertinent data.

2.1.3 GEOTHERMAL. It has long seemed logical to fly sensitive heat detectors over broad areas to search for surficial temperature and heat flow anomalies related to near-surface thermal sources during the first phases of exploration. Sensors on aircraft can detect temperature differences as small as 0.1° centigrade while those presently on spacecraft will pick out differences of about 0.5 to 1.0° centigrade (but at much lower spatial resolutions). An example of a well-defined thermal anomaly is shown in Figure 2. However, two types of problems combine to impose serious difficulties on the use of remote sensors to spot geothermal anomalies. First, the actual temperature differences between the surface above a heat source and the peripheral background is usually

reduced effectively to disclose valid anomalies. Among these are slope and topographic effects, soil moisture and density, wind and other atmospheric perturbations, and certain intrinsic thermal properties (e.g., emissivity) of the earth materials. Such corrections require field data, are often complex and unreliable, and are time-consuming and costly. In view of this, doubts about the use of satellite-mounted thermal sensors to detect geothermal anomalies persist, although some large anomalies (both in size and temperature differences) will likely come to light as more efficient sensors are developed. Aircraft mounted sensor surveys may offer better prospects, provided promising regions are initially chosen by other means.

2.1.4 COAL AND OIL SHALE. At present, the location and extent of most of the near-surface deposits of these two energy sources are quite well known in the U.S. Remote sensing for these sources in this country would generate few new supplies. The main application here will center about monitoring their extraction (strip mining) and the desired recovery of the environment thereafter.

The situation may be quite different in the less-explored, developing world. Exploration for coal and oil shale probably can derive some limited assistance from remote sensing although at present no clearcut model for using sensed data in the search has been defined. Certain rock types tend to occur stratigraphically with coal and, in some instances, might be detectable. Oil shale presumably has few characteristic surface manifestations, although topographic expression may be distinctive. One reported application of LANDSAT has been to observe seasonal changes in saline lakes (e.g., Lake Magadi in Africa) that are modern counterparts to the depositional and climatic environments of the past favoring oil shale development in order to better understand the conditions influencing the formation and distribution of these shales.

Current remote sensing research within the geological community is concentrating along two lines. First, the effects of selected, longer wavelength bands on improving discrimination and identification of rock and alteration types are undergoing assessment. A band centered at 1.65 μ is more sensitive to reflectances from rocks than from vegetation, and thus tends to subordinate the influence of grasses and other plants on the signal received from a mixed target. Differences among various, major rock types also seem to be accentuated. Another interval located in an atmospheric window between 2.15 and 2.45 μ responds to two important absorption bands centered around 2.20 μ (for OH^-) and 2.35 μ (for CO_2). A detector encompassing this interval will pick out both clay minerals (including some alteration products) and carbonates (limestones) if that interval is divided into two narrow bands that cut off near 2.30 μ . These two rock materials should be distinguishable from each other and from probably most other rock types. Second, new approaches to data processing appear to pinpoint certain types of alteration, often giving rise to distinctive patterns in alphanumeric or photographic outputs that are absent in standard renditions.

2.2 EXPLOITATION

This is focussed on improving the efficiency and safety of extracting, processing and transporting identified mineral resources. The use of satellite data products which assist in locating geological structures and in defining the structural controls of mineralization may also aid in the exploitation of some energy resources. Analysis of imagery in terms of structure, geomorphology and hydrology may provide information on possible railway, highway and pipeline routes, may assist in utilizing local transportation networks to their optimum and in selecting new routes from mine to processing plant or oil field to refinery, and may help in selecting locations for dams or canals.

With the increase in underground coal mining, LANDSAT imagery has proven to be of unique value for mapping fractures related to roof-falls. Color IR and LANDSAT imagery were used for mapping fracture systems in areas of Illinois and Indiana where roof-falls were known to be related to intersecting closely spaced fractures. Roof-fall hazard maps based on the remote sensing data have been prepared for mining areas of this region.⁸

The SKYLAB multispectral photographic camera (S-190A) and the earth terrain camera (S-190B)^{9,10,11} provided data valuable to surface mine planning and for reclamation activities. The high resolution of these systems permitting surface studies to be undertaken at scales of from 1:250,000 to 1:24,000. It was concluded that the SKYLAB data could be used in overall planning and management and for enforcement of regulations governing surface coal mining activities.¹² The major categories of strip mining properties (active, abandoned, undergoing reclamation and reclaimed) could be defined. Vegetation coverage could be estimated closely. Past stripping operations could be identified, as well as coal seams per se, spoil banks, refuse areas, ponds, impoundment quality, highwalls, access and haulage roads, unmined areas and some acid drainage effects. High altitude photography was combined with the SKYLAB imagery in some instances to obtain slope angles, not obtainable from the SKYLAB data.

Although, as far as the public record is concerned, remote sensing has yet to identify a new oil-field, it has had success in assisting in the development of oil and gas areas.¹³ The Columbia Gas Company reported the use of remote sensing in the development of the Haysi gas field of Virginia and Kentucky where the gas is obtained from naturally fractured sandstones. Faults were located through the use of black and white IR photography and side-looking radar (SLAR). It was determined that the fractures had an average dip of some 80° instead of vertical. Fifteen wells were drilled into the intersections of the reservoir rock and the fractures, proving to be twice as productive as the average wells.¹⁴ In the Eilanden Basin, a known petroleum area in the cloud covered jungle of Irian Jaya, SLAR was used to define structures related to drainage patterns, to identify volcanic or carbonate rock terrain by distinctive topography, to define specific depositional features and to map a major structural arch. The SLAR imagery defined the dimensions of the structural folds and company geologists selected those folded structures which were the more likely to persist at depth, identifying favorable areas for drilling.¹⁵

Water is essential to most mining and beneficiation. Short¹⁶ reported on serendipitous ground water discoveries such as the work by Goetz and others in Arizona which identified structural features in basalt caprock near Flagstaff which indicated favorable locations for drilling into the cavernous Redwall limestone, LANDSAT studies which led to the realization that the lavas on the Shivnitz Plateau filled old drainage in Moenkopi shales, and mapping on the Coconino Plateau in conjunction with enhanced LANDSAT imagery which revealed perched aquifers, sandstone lenses underlain by clay within the Kaibab limestone.

LANDSAT data products have also been used to identify likely sites for earth-filled dams, to locate glacial gravel deposits for use in road construction and has been effective in identifying new transportation routes. Remote sensing also has applications for identifying areas where erosion may be a factor, such as defining stream channels, embankments, arroyos and other features related to potential erodability. Such information is important to planning construction projects or for introducing measures to reduce potential erosion in mining areas or along access routes. A regional analysis or monitoring for potential geological hazards such as landslide prone areas or the location of fault traces is important for considerations of dams, pipelines, tunnels, bridges and power plants associated with mining areas. This would also include improved efficiency of hydropower generation through improved snow-melt and run-off predictions.

2.3 POWER PLANT SITING

Information can be provided to assist in balancing the conflict between the need to provide adequate electric power to meet regional requirements and the need to protect public safety and environmental quality. The relevant types of data include fault identification, assessment of usable water resources as coolants, assessment of land-use and ecological data, identification of possible geological hazards. Much of this would apply to hydroelectric plants (including system design for entire watersheds) as well as coal or nuclear plants. Power plants need to be located within reasonable distances of centers of population and the various real or imagined dangers emphasize the need for careful evaluations of the areas selected. LANDSAT imagery and aerial photography can provide much of the data needed to help assure an abundant supply of energy with due regard to environmental factors and public welfare.^{17 18 19}

Just as remote sensing may play an important role in exploration for energy minerals, many of the same techniques may be employed in defining faults and geologic hazards and other phenomena pertinent to selecting sites for power plants. Remote sensing also has the capability of determining relevant information on topography, soils, transportation routes, water supply, land use and local population distribution. Analysis of remote sensing data also has applications for assisting in locating possible areas for the disposal of waste materials and in some instances may be used to predict or to monitor the environmental effects of thermal and other effluents on regional hydrology and ecology, or the effects of construction or dredging debris introduced into river systems or coastal wetlands. Both satellite imagery and aerial photography have applications to power plant siting, but it is often the case that the synoptic scale of LANDSAT imagery may identify large linear features, often faults, that may not be identified on a patchwork of aerial photographs or which may be obscured at the proposed site area by the subsequent local deposition of sedimentary materials.

Wobber and Martin²⁰ have illustrated the remote sensing applications of a nuclear power plant siting methodology proposed by the Atomic Industrial Forum (AIF) in its National Environmental Studies Project.²¹ Wobber and Martin²⁰ provide a stage-by-stage analysis including geographic/demographic, engineering and environmental considerations.

LANDSAT is unique in its ability to locate water bodies such as lakes, rivers, estuaries and coastal features, and LANDSAT investigators have been able to significantly advance studies of surface hydrology. The panoramic nature of LANDSAT products also adds a real perspective to hydrologic data collected at point stations or from DCS platforms, the two sources providing valuable data on lake processes, drainage basin characteristics and changes, hydrologic controls, hydrodynamics and the distribution of snow and ice. LANDSAT also provides a basis for pertinent demographic and land-use studies, such as that compiled in the Dartmouth College Land-Use investigations of the Northern Megalopolis which produced thematic products showing eleven separate land-use categories of a three state area of New England.²²

Specific site selection requirements include an assessment of the natural history of a proposed area to determine if there are unique or endangered species of flora or fauna. Remote sensing may often help in defining the boundaries of specific ecological systems or may locate similar areas nearby where the specific species may also exist.

The analysis of topography, linears and other geologic structures may be undertaken on satellite data products. Physiographic configurations that are surface expressions of subjacent structure, stratigraphy or lithology can provide much information related to possible geologic hazards in potential site

areas. Such analysis of surface characteristics may indicate fracture zones, sink hole areas, broad areas where water might be impounded, areas where landslides or slumping might occur or has in the past, areas of recent valley fill which would preclude the establishment of major engineering projects, where an earthquake might produce serious stability problems or where there is evidence of subsidence.

Although the energy-producing technologies of hydroelectric power generation are usually socially and environmentally acceptable and do not often raise health and safety issues, the location of dams and the channelization of rivers may effect entire drainage systems, change water levels in streams and swamps, divert or capture water from other drainage routes and otherwise impact man, land use and biota. There are many important hydrological, geological, environmental and engineering problems inherent in hydroelectric plant siting which may be addressed through the applications of remote sensing data.

Similar to other plant siting, it is important to know about faults, geologic hazards, possible areas of flooding, local drainage and physiographic constraints. In addition, hydroelectric plants usually require reservoir storage, dams, tunnels, diversionary canals and other construction which is subject to careful geological analysis. The nature of soils, their water content, the fracture patterns in bedrock or the dip and strike of regional strata are essential ground truth considerations. There is, unfortunately, a long history of dam and bridge failures because of poor site selections.

In much of the world the water required for irrigation and municipal use originates in mountainous areas as snowfall. Remote-sensing-assisted snowline surveys, estimates of snowpack and the use of satellite-linked, data collection devices may provide essential information for predictive modeling of regional run-off and stream flow. Estimates of the routes, amounts and timing of run-off is important to reservoir management and for allocations of water resources for industry, agriculture and municipal supply. The reduction of standard error of streamflow forecasting through the application of hydrological and geomorphological relationships obtained from satellite imagery will help optimize power generation and reduce flood risk.

Hydrologic parameters of watersheds for use in models to predict run-off are difficult to quantify using conventional methods; however, remote sensing techniques may often quantify vegetative, soils and soil moisture data rapidly and economically.²³ Ten watersheds of the Chickasa, Oklahoma area were tested using LANDSAT data techniques, producing more accurate runoff coefficients than obtainable by conventional methods. Similar tests were made in a dry season for 22 subwatersheds of the same area where flood detention structures had been built. Again, predicted values were more accurate than those produced by conventional methods. The New England Division, Corps of Engineers undertook a two year study to assess LANDSAT usefulness in the operation of its water resources system used in flood control. It was concluded that real time data collection by LANDSAT was both feasible and reliable, and far less expensive than conventional methods.²⁴ In the western United States where snow water is depended upon for power generation, irrigated agriculture and reservoir regulation, the importance of accurate runoff information from satellite observations has been recognized by several agencies. An early recognized problem was the assessment of snowlines in heavily forested areas. Rango, Salomonson and Foster²⁵ report a simple method of the overexposure of diazo esochrome film which allows enhancement of the contrast between forests with and without snow, which may be used in snow mapping, and which is important to estimations of seasonal streamflow and for hydroelectric power plant site selection.

2.4 ENVIRONMENTAL MONITORING AND ASSESSMENT

This would cover monitoring parameters related to health, safety and environmental conditions. Included are acid run-off from coal mining, thermal effects of power plant coolant water, gaseous and particulate effluents from coal-fired power plants, and the monitoring of strip mining and associated land restoration. While much can be done to eliminate or control, other consequences of increased electric power generation, the most serious threat appears to be the CO₂ produced by vastly increased fossil fuel combustion and its possible effect on global climate through the greenhouse effect. It would appear that satellite based remote sensing could make a significant contribution to global CO₂ monitoring. Many of the environmental applications of remote sensing are included in 2.1 and 2.3 above.

2.5 TRANSPORTATION INFRASTRUCTURE

Improved mapping and monitoring could provide the capability to ensure the design and operation of minimum--energy transportation networks. This concept has, surely, more application to developing countries where the infrastructure is, for the most part, not already in place--but more about that shortly. Many aspects of this remote sensing application are included in the discussions of 2.1, 2.2 and 2.3 above.

3. ENERGY-RELATED REMOTE SENSING FOR DEVELOPING COUNTRIES

In the context of the energy "crisis" and ever-increasing energy prices, the plight of the non-OPEC developing world deserves some special attention. Many of us involved in remote sensing have felt that developing countries (LDC's) could anticipate a quantum jump in economic planning capability from remote sensing. This is due largely to the relatively low level of information that many developing countries have traditionally had to start with. LANDSAT-assisted mapping and monitoring can provide a tremendous boost as indicated by a number of studies sponsored by the Agency for International Development (AID).²⁶ There is little doubt that the same potential applies to energy related problems and includes all of the five aspects just discussed.

The non-OPEC LDC's spend 10's of billions annually on petroleum products and fertilizers. The discovery of oil and/or fertilizer minerals in LDC's would go a long way toward redressing their severe trade deficits brought about by petroleum price increases, as well as addressing their specific need to significantly increase energy consumption.

Efraim Friedmann, World Bank energy expert stated in regard to developing countries in general, and to Latin American countries specifically²⁷ (in part): "... the trade-off among developed countries between conserving energy and increasing energy supplies is not relevant to Latin America.

"... if the reason is to improve the standard of living of its people, it must register high economic growth, which in turn means it will have to consume more energy. Additionally, since most of Latin American energy is used for industrial purposes rather than private transportation and home heating...any efforts to conserve energy will not only curb its industrialization process but will slow down economic growth as well.

"Latin America must speed up exploration and development of conventional energy sources...the region is largely a virgin area regarding exploration for oil gas and coal." He also noted the growing energy crisis in the rural areas where some 80 percent of energy is derived from fire wood and agricultural waste, and where these supplies are decreasing due to deforestation. It is possible that remote sensing of the biomass in such areas could locate significant sources of non-commercial fuel materials for local use.

In recognition of some of the special problems of developing countries, the NEP Budget for ERDA includes a \$6 million increment for non-nuclear energy technology assistance to these countries. These efforts could be aimed at: identifying and analyzing the specific energy needs of selected countries; exploration for indigenous energy resources; appropriate technologies to meet rural and urban needs; large-scale technologies such as hydroplants, geothermal, and direct coal combustion.

The fifth item, the design and implementation of energy-efficient transportation infrastructures, is an opportunity which developing countries, with the assistance of remote sensing, should be able to exploit much more effectively than the developed world.

4. CONCLUSIONS AND RECOMMENDATIONS

If we examine side-by-side the thrusts of the National Energy Plan (NEP) and contributions which remote sensing might provide, it appears that the five points discussed before apply--even with more intensity than before. However, there appear to be three specific applications which we would commend to the remote sensing community as worthy of immediate pursuit. Others exist, such as applications for geothermal anomalies and hydropower optimization, but the following appear to be the major NEP-related thrusts:

First--and foremost--is the acknowledged need to improve the accuracy of our knowledge of uranium reserves and resources. The nation's new nuclear power policy--which indefinitely postpones the breeder and fuel reprocessing--essentially commits us to a dependence on "once-through" uranium for the balance of this century, and a role as a supplier of enriched uranium to that part of the world which cooperates in our non-proliferation objectives. Uranium resource estimates currently vary from 1.8 million to 3.7 million tons. Alaska, for example, may well be significantly under-represented in these estimates of U.S. uranium resources. The directed--and necessary--re-orientation of the National Uranium Resource Evaluation (NURE) program will require a sharpening of its uranium resource assessment as well as extending its purview to include thorium resources. Interest in global assessments would also increase. Remote sensing should have an increased role in designating favorable areas for both national and international exploration. This should be taken as a further challenge in the remote sensing community, particularly with LANDSAT type data, to assist NURE in its now even more difficult assignment.

Second, the greatly intensified use of coal for electric power generation may have an impact on global climate which makes imperative measuring and monitoring of CO₂ distribution in the atmosphere. This should be a challenge to NOAA and to the NASA Earth Observations Program to develop effective satellite-borne CO₂ instrumentation. The sooner the better since baseline data will be needed in order to measure change, regardless of which models are used.

Thirdly, the requested enactment of tough, uniform Federal strip mining legislation creates an opportunity for LANDSAT and high-altitude aircraft capability in the identification and monitoring of both strip mining and the effectiveness of land restoration.

Overall, it appears that many of the difficulties in implementing the NEP may be related to various uncertainties--in resource assessments, in environmental parameters, and in the data needed for regulatory enforcement. The remote sensing capabilities of satellites and aircraft represent powerful, and perhaps as yet under-utilized, tools to reduce these uncertainties and hence facilitate the successful implementation of the NEP.

Table 1: FY 78 NEP REVISIONS TO ENERGY BUDGET
(Budget Authority - \$ in Millions)

<u>Program</u>	<u>Ford Budget Jan 1977</u>	<u>Carter/NEP April 20, 1977</u>	<u>Change</u>
Conservation	158	325	167
Fossil Energy	598	657	59
Solar Heating & Cooling	45	96	51
Solar Electric	260	224	(36)
Geothermal	88	101	13
Fusion	513	433	(80)
LMFBR	855	483	(372)
Nuclear Fuel Cycle & Safeguards	636	587	(49)
Other Fission	148	153	5
TOTAL	<u>\$3,301</u>	<u>\$3,059</u>	<u>(242)</u>

Table II: REMOTE SENSING APPLICATIONS TO ENERGY

- (1) EXPLORATION
 - Uranium
 - Oil, Gas
 - Geothermal
- (2) EXPLOITATION
 - Extraction
 - Processing
 - Transporting
- (3) POWER PLANT SITING
 - Fault Identification - Other geological hazards
 - Water needs
 - Effluents
- (4) ENVIRONMENTAL MONITORING AND ASSESSMENT
 - Strip mining - Land restoration
 - CO₂ monitoring
 - Acid run-off
- (5) TRANSPORTATION INFRASTRUCTURE
 - Energy efficiency
 - Developing countries

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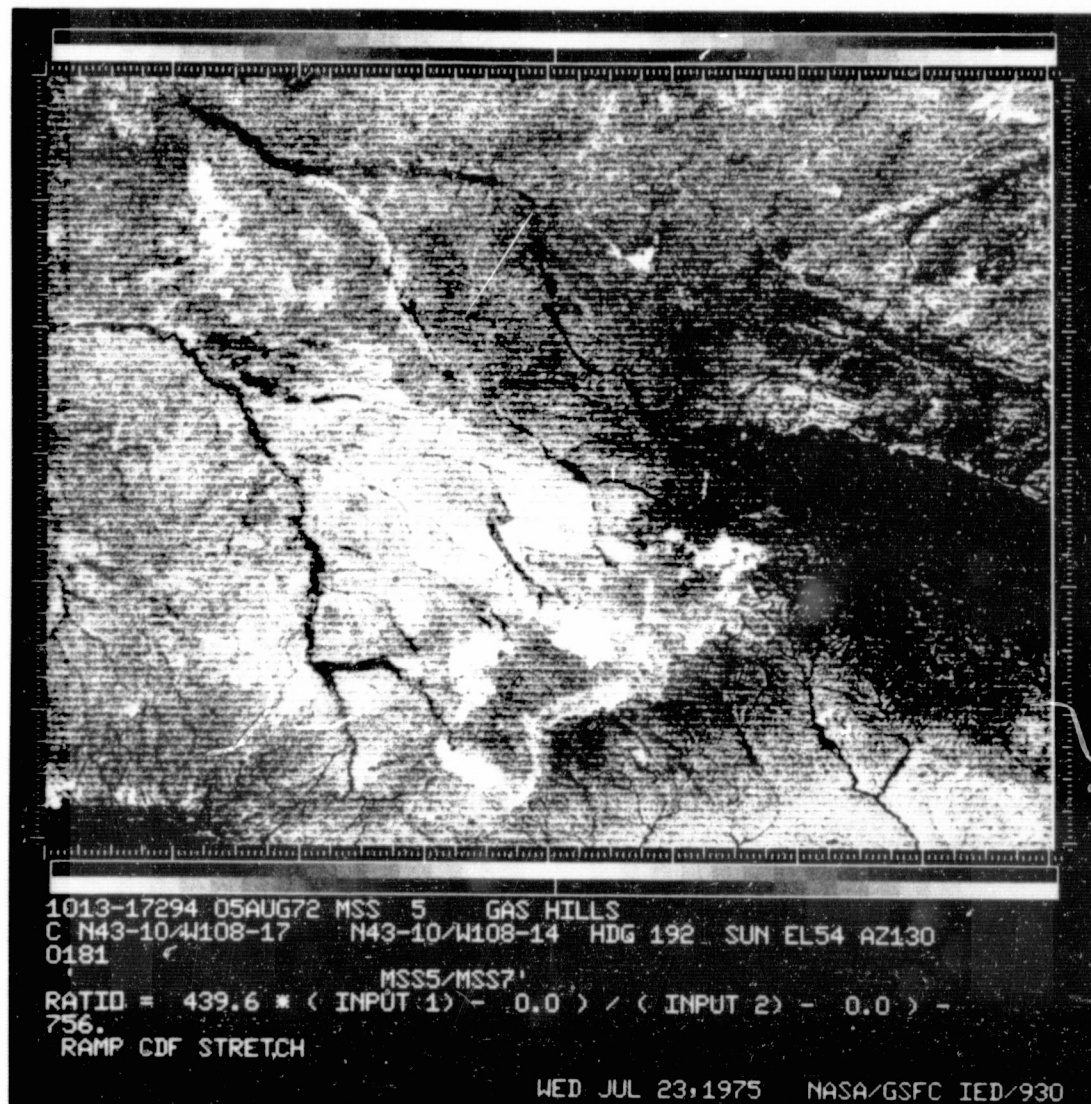


Figure 1: A band ratio image made from band 5 over 7 (5/7) using part of Landsat scene 1013-17294. In this rendition, the open pits in the Gas Hills uranium district within the Wind River basin of Wyoming are displayed in whitish tones. However, some surface manifestations of hydrated iron oxides - often a guide to uranium roll deposits - are also presented in very light tones. Color ratio composites reduce this ambiguity. Color composites made from principal components analysis images show the iron oxides in distinctive colors separable from most other surface features. Length of image corresponds to 40 km on the ground. Courtesy N. M. Short.

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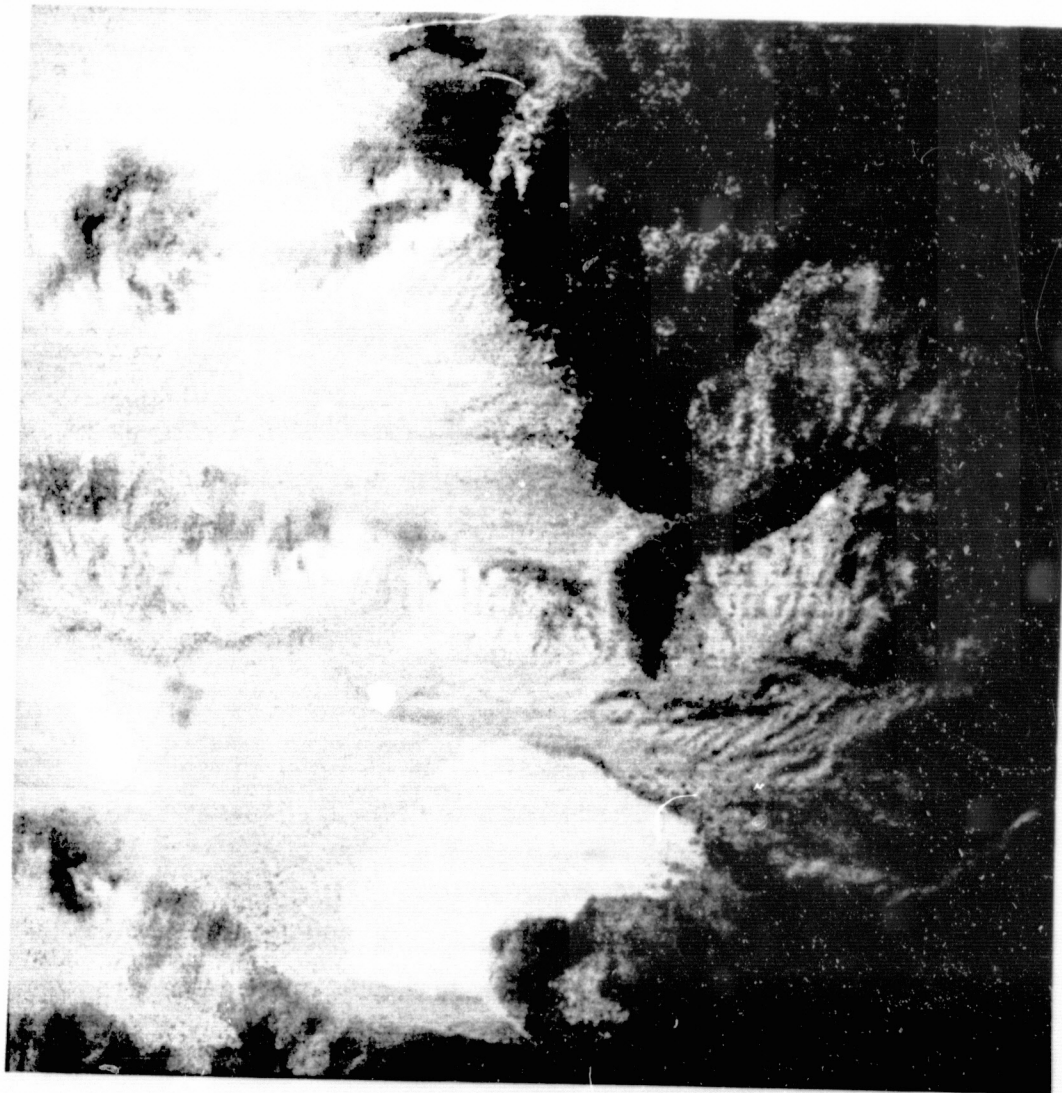


Figure 2: Black and white print made by computer enhancement (stretching) of digital data obtained by the Bendix 24-channel scanner during an air flight over the Roosevelt geothermal anomaly in southwest Utah. This image depicts the terrain as sensed in channel 15 (4.7 μm) in which the emitted thermal signal greatly exceeds the reflected signal. At bottom center is a bright (light-toned) fan-shaped area which is believed to correspond to one of the thermal anomalies associated with a hot springs. Scene about 4 km wide (long dimension). Courtesy N. M. Short.

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LANDSAT-D THEMATIC MAPPER SIMULATION
USING AIRCRAFT MULTISPECTRAL SCANNER DATA*

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ABSTRACT

A simulation of imagery from the upcoming LANDSAT-D Thematic Mapper was accomplished by using selected channels of 24-channels aircraft multispectral scanner data. The purpose was to simulate Thematic Mapper 30-meter resolution imagery and compare its spectral quality with the original aircraft MSS data and determine changes in thematic classification accuracy for the simulated imagery. The original resolution of approximately 7.5 meters IFOV and simulated resolution of 15, 30, and 60 meters were used to indicate the trend of spectral quality and classification accuracy. The study was based in a 6.5 square kilometer area of urban Los Angeles having a diversity of land use.

The original imagery was reduced in resolution by two related methods: pixel matrix averaging, and matrix smoothing with a unity box filter, then matrix averaging. Thematic land use classification using training sites and a Bayesian maximum-likelihood algorithm was performed at three levels of standard deviation - 1.0, 2.0, and 3.0 sigma. Plots of relative standard deviation showed that for larger training sites, with a normal distribution of data, as the resolution decreased, the distribution range of density values decreased. Also, as resolution decreased, classification accuracies for three levels of standard deviation increased. However, the indication is that a point of diminishing returns had been reached, and 30 meters IFOV should be the best for multispectral classification of urban scenes.

A simulation of imagery from the upcoming LANDSAT-D Thematic Mapper had three purposes: 1.) to simulate the Thematic Mapper imagery using aircraft multispectral scanner (MSS) data by image processing techniques; 2.) to determine the spectral quality of the simulated imagery by comparing the spectral characteristics of the original imagery and simulated imagery at three different resolutions, including the 30-meter Thematic Mapper resolution; and, 3.) to determine the accuracy of thematic classification by using a hybrid Bayesian maximum-likelihood classifier and comparing classification results from the original and simulated images.

Since 1972, the LANDSAT satellites have been recording the earth and its changes every 18 days for scientists. Based on the results of research already performed, a second generation satellite scanner would be very useful. The Thematic Mapper is the proposed scanner, scheduled for launch in the early 1980's with LANDSAT-D. At the present time, satellite observations are being made at a spatial detail of one and a half acres in four regions of the electromagnetic spectrum. With the Thematic Mapper, the resolution will be increased to approximately one-fifth of an acre. The Thematic Mapper will also be more sensitive to electromagnetic wavelength variations. Because of the increased sensitivity, scientists and planners should be better able to accomplish specialized applications, such as, identify surface materials in urbanized areas, detect differences in soil moisture, and better distinguish crops in areas of diversified farming around the urban fringe.

The simulation utilized aircraft 24-channel multispectral scanner data of the Los Angeles area, flown November 14, 1973. The flight line chosen for the Thematic Mapper simulation was flown at 3350 meters (11,000 feet) on a relatively smog-free day. The quality of the data was acceptable in the visible and near infrared ranges, however, data in the middle and thermal infrared ranges were too irregular or poor in quality to use.

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Johnson Space Center (JSC) reported that at least three types of noise could be present in the 24-channel MSS data: Least significant bit problems probably caused in the analog to digital data conversion and shown by an overabundance of even or odd density values; drift and oscillation in gain; and, saturation at either extreme of the density value histogram, indicating that gain and/or offset controls on the scanner were set improperly.

The scanner data used showed a three to one predominance of odd density values over even density values. No periodic fluctuations in data were indicated by one-dimensional fourier transforms that were performed perpendicular to the scanlines. There was no saturation in density values.

A signal-to-noise ratio test run by JSC over 300 scanlines of the Los Angeles mission indicated that less than optimal ratios were present. Of the five channels tested (corresponding to those used in this simulation) all five showed ratios of between 20 to 1 and 30 to 1. 200 to 1 is considered an optimal signal-to-noise ratio.

The scale of each resolution cell or, picture element, was about 7.5 meters square. Even though the IFOV of each scanner element was 2.5 milliradians, which means a resolution cell of 8.4 meters square from an altitude of 3350 meters, there was overlap of cells, reducing the scale. The actual scale of closer to 7.6 meters square was figured from a comparison of the image to 7.5 minute U.S.G.S. topographic quadrangle sheets, however, the scale was rounded to 7.5 meters to provide a more workable set of multiples - 15, 30, and 60.

The selection of bands for the Thematic Mapper simulation was based on the spectral correspondence between the proposed LANDSAT-D Thematic Mapper data and the 24-channel aircraft MSS data (Table A). MSS channel 3 was not used because the effect of atmospheric conditions was too strong. Channel 12 data showed too much noise. The sensors for channels 20 and 21 were not operating correctly. Fortunately, channels 4, 5, 6, 8, and 9 were useable. To simulate the green band more closely, channels 4 and 5 were combined by averaging. The near infrared was simulated by averaging channels 8 and 9. Therefore, the Thematic Mapper was simulated using three bands of data - green, red, and near infrared - with an intermittent range of .53 to .87 microns.

The study area, in the Lincoln Heights district just northeast of downtown Los Angeles, was chosen for a number of reasons. This 1973 flight was the only low altitude MSS data available. Although several flightlines were flown over the Los Angeles Basin during the mission, the particular study area was relatively close to JPL and contained a diversity of land use, including residential, commercial, industrial, institutional, parks, transportation networks, and vegetation (Figure 1). Shadows caused by steep slopes and tall buildings were avoided as much as possible, while retaining the variety of land use. The study was centered along the flightline to minimize spatial distortions and loss of data because of panorama effects.

A land use inventory map of the study area was made by air photo interpretation and field mapping. The inventory map was used as a base for identifying representative examples of each land use class, called training sites, for the computer classifier. The inventory map also served as a basis of visual comparison for the computer-generated classification maps.

Land use classes chosen for the simulation were: residential, commercial, industrial, institutional, park, vegetation, and undefined. Residential included single-family houses, older multiple-family, multiple-story houses, and more modern multiple-unit apartment buildings, all with varying amounts of domestic vegetation. Commercial was for the most part strip commercial along major streets. Corner grocery stores within residential areas were regarded as too small and too integral to the residential landscape to be included with commercial. The industrial class included railroad yards, warehouses, stockpiles, and manufacturing sites. The institutional class included schools, hospitals, and churches. Parks were public green spaces with maintained grass and trees. Vegetation included hillside growth, mostly non-domestic grasses. Undefined included freeway, major streets, and water reservoirs.

Land use training sites - representative examples of the land uses - were delineated on the image. The training sites were chosen so they would define the same area on the ground regardless of the resolution. The density values within the training site boundaries are used to compile statistics that represent the land use class. These spectral statistics were used by the thematic classifier to find other picture elements in the image representing the same land use. Each land use class was represented by one or more training sites (Figure 1):

Residential - left center and lower right
Commercial - two in upper left center

Industrial - upper left, two in lower left, and lower right border
 Institutions - hospital in lower middle
 Park - right center
 Grassland - two in upper right
 Undefined - including freeway and major streets

The original 7.5 meter resolution image was reduced in spatial resolution to simulate Thematic Mapper resolution at 30 meters. The image was also reduced to 15 and 60 meters so that the resolution series of 7.5, 15, 30, and 60 meters would help indicate trends in spectral quality and classification accuracy. Two reduction methods were used: Matrix averaging, and matrix smoothing, then averaging.

With matrix averaging, an input matrix of picture elements was averaged. For 15 meters resolution, the matrix was 2 picture elements by 2 picture elements. For 30 meters it was 4 by 4. And for 60 meters it was 8 by 8. All the elements of the output 4 by 4 matrix, for example, were given the value of the matrix average (Figure 2).

After the first matrix, the computer algorithm advanced to the next matrix to average its elements and continued as such until all matrices had been averaged. The result of the averaging process was a set of 7.5, 15, 30, and 60 meter resolution images for comparison (Figure 3). The second method smoothed the scene with a unity box filter and then averaged the matrices (Figure 4). The initial smoothing was the result of a moving matrix that averaged elements within the matrix and assigned the average to the center element. Following each averaging operation, new elements on the leading edge were incorporated, and another matrix average calculated. The output image was composed of individual average picture elements which then became the input for matrix averaging, the first method. The second method resulted in a set of 15, 30, and 60 meter resolution images that have less distinctive in tone and definition because of the smoothing. The reduction methods tended to smooth out the effects of noise in the data by averaging. The reduction methods also helped reduce the confusion of too much detail in the 7.5 meter resolution.

Statistics were compiled from within the training site boundaries for all the resolutions produced by both spatial resolution reduction methods. The means and standard deviations were used by the Bayesian maximum-likelihood classifier to create the final classification maps. The classifier provided a decision-making rule that calculated the maximum probability that a certain picture element, in all bands, was a particular land use. The output picture element was then coded as the land use. The decision rule was based on the mean and standard deviation statistics of the class training sites.

The results of the classification process showed the effects of resolution and the standard deviation decision rule (Figure 5 and 6).

Generally, land use patterns shown by the computer-generated classification maps compared favorably with the land use inventory map (Figure 7), except for problems with the commercial, industrial, and institutions classes. Confusion was especially introduced with the hospital training site that included large areas of diverse rooftops, shadows, and vegetation, generating a much too wide spectral range that easily corresponded with other classes. The classified image shown with the inventory map (Figure 7) was the best classification visually, showing relatively homogeneous land use patterns with minimal stray dots. It is the 3.0 sigma classification of the 30-meter resolution image produced by matrix smoothing and averaging.

To evaluate the spectral quality of the simulated imagery and evaluate the accuracy of thematic classification, several comparison plots were made. The plots of relative values showed changes in standard deviation or classification accuracy as percentages (Figure 8, 9, and 10). For instance, the plot of relative changes in standard deviation for changes in resolution, for a residential training site (Figure 8) showed a progressively decreasing relative sigma. The standard deviations for the red (RED), green (GRN), and near infrared (NIR) bands of the matrix-averaged 15-meter resolution (15A) were about 70% of the original 7.5-meter resolution. The three bands of the smoothed-then-matrix-averaged 15-meter resolution (15B) had sigmas of between 40% and 50% of the original 7.5-meter resolution.

Classification accuracy was measured as the percentage of a particular land use training site that was actually classified by the computer as that land use. Spurious land use classifications within a training site, with their spectral characteristics different from the prevailing land use were classified differently from the expected. Such misclassification was reported as lower relative accuracies that increased with a decrease in resolution.

The residential training site had a larger number of data points that were distributed in an approximately normal manner. With normal distributions, the computer classifier was capable of accurate results as evidenced by the comparison plot (Figure 8). The industrial training site, (Figure 9) with a bimodal distribution of density values, had relative classification accuracies that were much lower, indicating confusion with other classes. An interesting surge between the two 60 meter resolutions probably said more about the smoothing method of resolution reduction than about the relative classification accuracy. A considerably smaller city park training site showed more erratic results (Figure 10). As the resolutions decreased the problem of too few data points showed as unreliable information on relative standard deviations and relative classification accuracies.

The low accuracy levels in the industrial training site not only indicated a classification problem with bimodal distributions, but also indicate a basic problem of defining land use classes. There tends to be confusion between commercial, industrial, and institutional land uses in thematic classification because the physical or spectral characteristics of a land use do not always divide as sharply as the cultural definitions of the land use. For example, under certain circumstances, all three land uses tend to have ample paved spaces adjacent to major buildings which tend to have large uninterrupted expanses of rooftop. The buildings cast expanses of shadows, especially with multiple story units. Large areas of relatively homogeneous materials, such as pavement, roofs, or shadows provide a relatively narrow range of spectral response for individual material, but a multi-modal range of response for the training site. Therefore, it is quite possible for training sites for commercial, industrial, and institutional to contain similar spectral characteristics which confuse the classifier. Perhaps the only real solution for improving the accuracy of classification for commercial, industrial, and institutional land use is to insure that the sensor has a wide selection of spectral bands, each band with a discrete wavelength range significantly separate from adjacent bands. It is also important to delimit training sites with a fairly homogeneous example of a class, but this requirement can be difficult when seeking a site with sufficient data points.

In summary, for the larger training sites with a normal distribution of data that retained a significantly large number of picture elements, as the resolution decreased, the distribution of density values in each band, as shown by standard deviation, decreased. Also, as resolution decreased, classification accuracies, for three levels of standard deviation, increased. The apparent increased classification accuracy of 60 meters over 30 meters may be misleading. For large training sites with an approximately normal distribution, the trend of the curve describing relative classification accuracy tended towards a significantly shallower slope at 60 meters. The indication is that a point of diminishing returns had been reached, and 30 meters should be the best for multispectral classification of urban scenes.

* This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract NAS7-100, sponsored by the National Aeronautics and Space Administration.

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THEMATIC MAPPER

BAND	RANGE (IN MICRONS)
1	.45 to .52 (BLUE)
2	.52 to .60 (GREEN)
3	.63 to .69 (RED)
4	.76 to .90 (NEAR INFRARED)
5	1.55 to 1.75 (MIDDLE INFRARED)
6	10.40 to 12.50 (THERMAL INFRARED)

24-CHANNEL MSS

CHANNEL	RANGE (IN MICRONS)
3	.46 to .50
4+5	(.53 to .57) + (.57 to .63)
6	.64 to .68
8+9	(.76 to .80) + (.82 to .87)
12	1.52 to 1.73
20+21	(10.10 to 11.00) + (11.00 to 12.00)

IFOV

30 METERS (EXCEPT 120 METERS
FOR BAND 6)

IFOV

APPROXIMATELY 7.5 METERS
ALONG FLIGHTLINE (FROM
3350 METERS ALTITUDE)

TABLE A
Spectral Correspondence between proposed LANDSAT-D Thematic Mapper Data and 24-channel Aircraft Scanner.

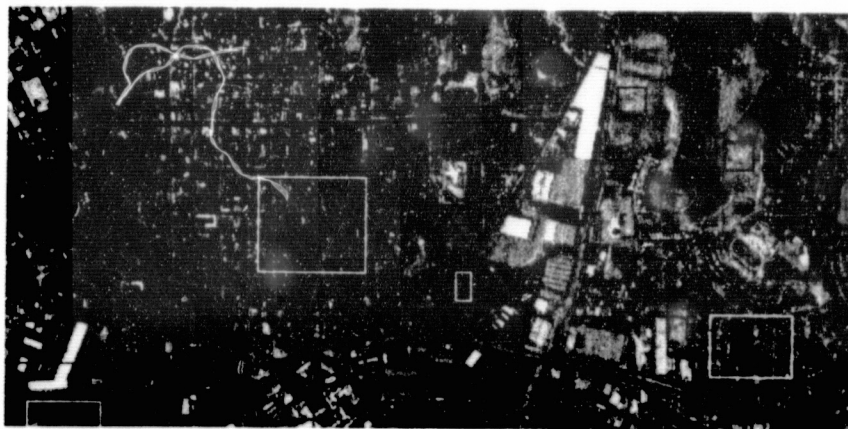


FIGURE 1
Training Sites Outlined on MSS Image

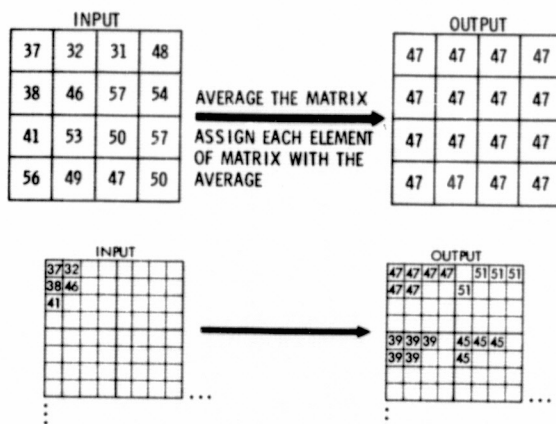
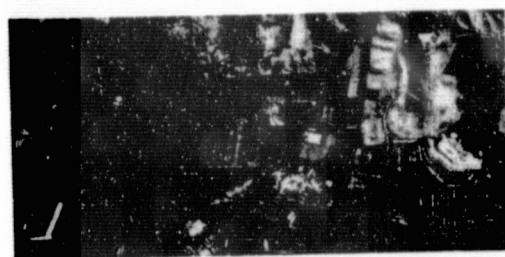
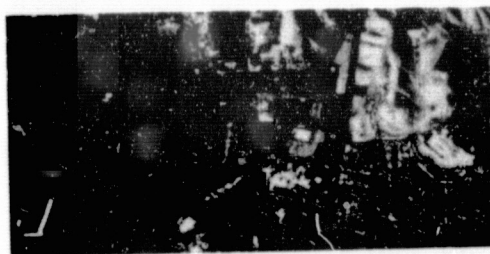


FIGURE 2
Matrix Averaging Method for Reducing Spatial Resolution



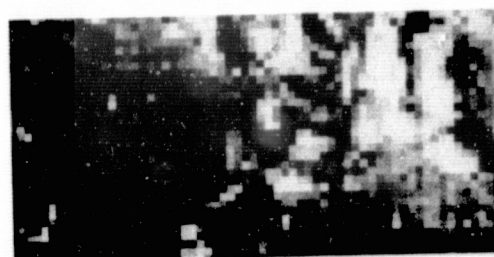
7.5 Meter



15 Meter



30 Meter



60 Meter

FIGURE 3

Comparison of 7.5 Meter to 15, 30, and 60 Meter Resolutions of Matrix Averaging Method

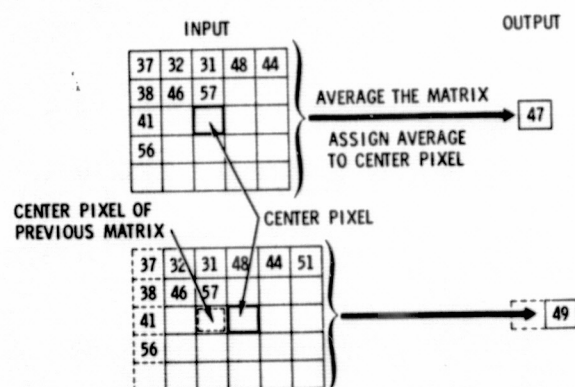


FIGURE 4

Matrix Smoothing, then Averaging Method for Reducing Spatial Resolution

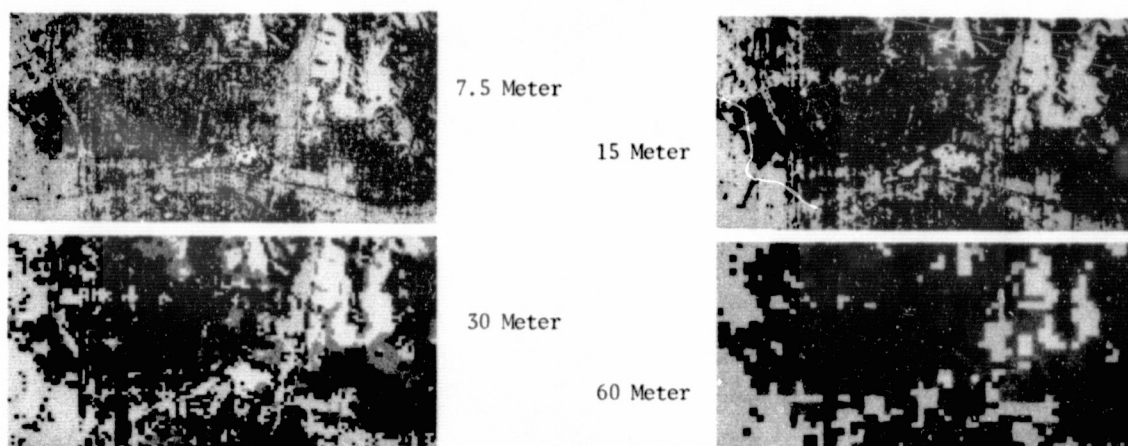


FIGURE 5

Classification Results for All Resolutions (from the Matrix Smoothing, and Averaging Method) Using a Standard Deviation of 3.0

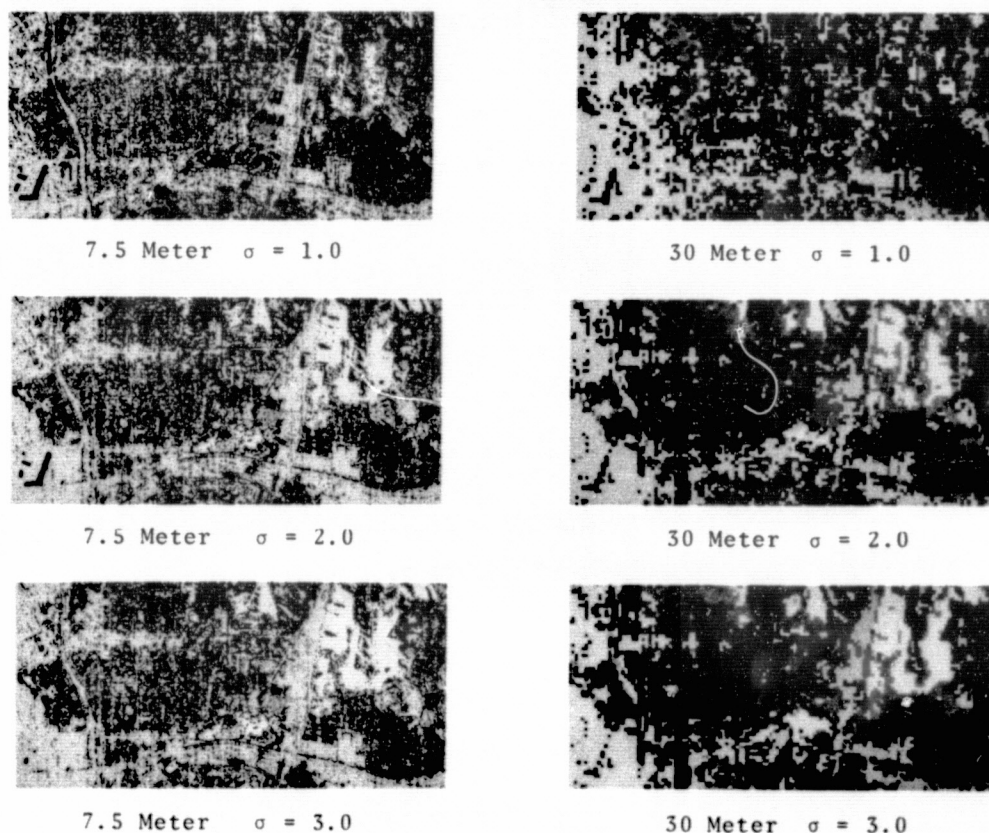
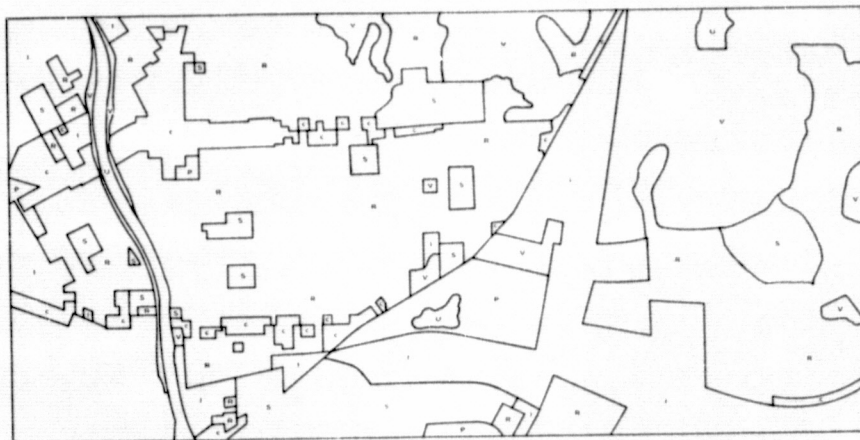
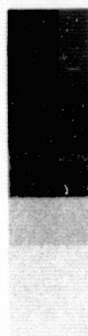


FIGURE 6

Classification Results for 7.5 Meter and 30 Meter Resolutions (from the Matrix Smoothing and Averaging Method) Using Three Different Standard Deviations.



LEGEND:



UNDEFINED - U
 RESIDENTIAL - R
 COMMERCIAL - C
 INSTITUTIONAL - S
 INDUSTRIAL - I
 PARK - P
 GRASSLAND - G



FIGURE 7
 Comparison of Computer-generated Land Use Map With Land Use Inventory Map.

FIGURE 8
Comparison Plot Between Relative
Classification Accuracies for A
Residential Training Site.

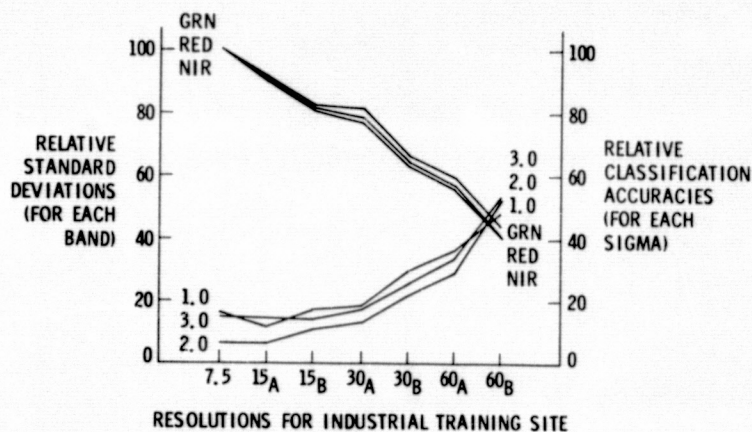
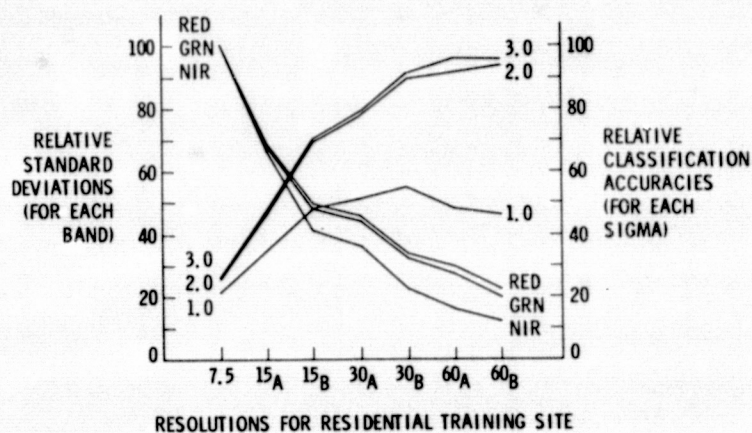
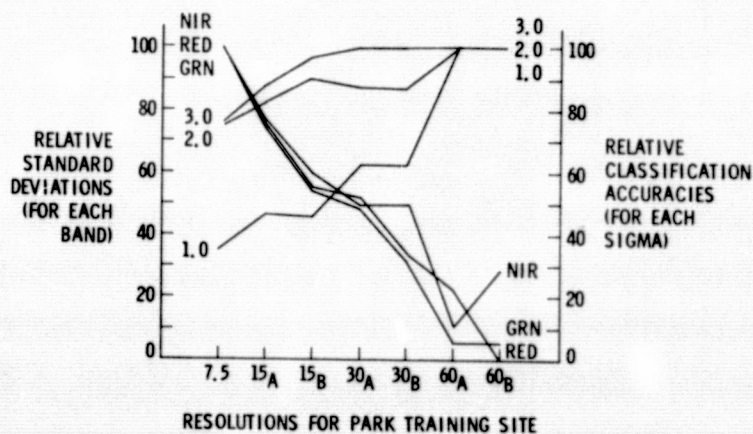


FIGURE 9
Comparison Plot Between Relative
Classification Accuracies For An
Industrial Training Site.

FIGURE 10
Comparison Plot Between Relative
Standard Deviations and Relative
Classification Accuracies For A
Park Training Site.



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USE OF NEAR INFRARED/RED RADIANCE RATIOS FOR
ESTIMATING VEGETATION BIOMASS AND PHYSIOLOGICAL STATUS

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ABSTRACT

The application of photographic infrared/red (ir/red) reflectance or radiance ratios for the estimation of vegetation biomass and physiological status were investigated by analyzing in situ spectral reflectance data from experimental grass plots. Spectral reflectance data were collected in June, September, and October. In addition, canopy biological samples were taken for total wet biomass, total dry biomass, leaf water content, dry green biomass, dry brown biomass, and total chlorophyll content at each sampling date. The normally collected spectral reflectance curves were multiplied by a spectral irradiance function to yield a spectral radiance curve for each plot sampled. Hypothetical red and photographic infrared sensors were simulated by integration of the narrow bandpass (0.005 μm) spectral radiance data for the regions of 0.63 - 0.69 and 0.75 - 0.80 μm , respectively. The integrated red and photographic infrared radiances were subsequently regressed against the various canopy or plot variables to determine the relative significance between the red, photographic infrared, and the ir/red ratio and the canopy variables. Several transformations of the red, photographic infrared, and ir/red ratio were also evaluated. These included the ir + red sum, the ir - red difference, the red/ir ratio, the vegetation index (VI) of $(\text{ir} - \text{red})/(\text{ir} + \text{red})$, and the transformed vegetation index (TVI) of $\text{VI} + 5$.

Several conclusions were drawn as a result of this analysis which have application to aircraft, satellite, and ground collected ir/red spectral data: 1) The ir/red ratio is sensitive to the photosynthetically active or green biomass, the rate of primary production, and actually measures the interaction between the green biomass and the rate of primary production within a given species type; 2) The ir/red ratio resulted in improved regression significance over the red or the ir radiances taken separately; 3) Only slight differences were found between ir/red ratio, the ir-red difference, the VI, and the TVI; 4) The asymptotic spectral radiance properties of the ir, red, ir/red ratio, and the various transformations were evaluated. It was found for the June data that the red radiance asymptotated at 2 to 3 times lower biomass levels of the canopy variables than the ir radiance. The ir/red ratio, the ir-red difference, the VI, and TVI were found to have similar asymptotic properties which were a function of the red and ir components' asymptotic properties. The ir/red ratio and the various transformations were found to be useful in estimating canopy variable total dry biomass, for example, up to $\sim 4000 \text{ kg/ha}$. Beyond that level, the ir radiance was more useful by itself; 5) No difference was found for different ir bandwidths when used in the ir/red ratio and the transformations. The regression significance was found to be extremely similar for the different ir bandwidths of 0.75 - 0.80, 0.80 - 0.90, and 0.75 - 0.90 μm when ratioed with the red radiance or used in the various transformations.

NOTE

The author unfortunately undertook a manuscript which was too lengthy for the 11th International Symposium proceedings. The paper in question, totalling ~65 typed pages, will be referenced here as a NASA X-document. Interested readers are encouraged to write to the author for reprint requests.

As such, only the abstract, conclusion and previously mentioned reference will be presented here.

Summary and Conclusions

1. The ir/red ratio, radiance difference, VI, and TVI are sensitive to the photosynthetically active or green biomass, the rate or degree of primary production within a given species type. Sufficient green vegetation must be present in the canopy for the ir/red ratio or the related ratio techniques to be useful.
2. The ir/red ratio, radiance difference, VI, and TVI showed improved regression significance over the red or the ir radiances taken separately when adequate amounts of green vegetation were present in the canopy.
3. Only slight differences were found between the ir/red ratio, radiance difference, VI, and TVI when regressed against the various canopy variables. The radiance difference, VI, and TVI were found to be the most useful. No advantage was found for transforming the VI into the TVI.
4. The asymptotic spectral radiance properties of the red radiance, ir radiance, ir/red ratio, radiance difference, VI, and TVI were evaluated for the June data. The red radiance asymptoted at 2 to 3 times lower amounts of the canopy variables than the ir radiance. The ir/red ratio, radiance difference, VI and TVI were found to have similar symptotic properties which were a function of the red and ir radiance components' asymptotic properties.
5. The regression significance for the different ir bandwidths of 0.75-0.80, 0.80-0.90, and 0.75-0.90 μm was evaluated and found to be extremely similar when ratioed with the red radiance or used in the various transformations.
6. The degree of nonlinearity between the red radiance, ir radiance, ir/red ratio, radiance difference, VI, and TVI and the canopy variables total wet biomass, total dry biomass, leaf water content, dry green biomass, and total chlorophyll content were directly related to the amount of green vegetation present. The accumulation of standing dead vegetation in the canopy had a linearizing effect upon the red and ir spectral radiances and the canopy variables.

Reference

Tucker, C. J., 1977. Use of near infrared/red radiance ratios for estimating vegetation biomass and physiological status. NASA X-Document, Goddard Space Flight Center, Greenbelt, Maryland 20771. 70 pages.

A STUDY OF SUSPENDED SOLIDS IN THE REQUENADAM BY REMOTE SENSING

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ABSTRACT

Remote sensing was applied to a preliminary study of suspended solids in the Requena Dam. Aerial and terrestrial photographs were analyzed by photointerpretation and microdensitometry. Field measurements and sampling were also made. A relationship between ground data for the concentration of suspended solids and the transmissibility of the aerial infrared film was suggested.

1. INTRODUCTION

Remote Sensing techniques (helicopters, aircrafts and satellites equipped with cameras and scanners) have been used in studies of water quality, and have been found useful as a complement of sampling and "in situ" data (physical, chemical, biological and bacteriological). This combination and the automatic analysis of the remote sensor data form one of the more complete and efficient methods for space-temporal detection and quantification of some parameters as suspended solids, temperature and turbidity which determinate the water quality. Four sample points near the edge were selected in the preliminary study of the Requena Dam. The remote sensor was aerial color infrared photography. Measured at the sample points were: pH, environmental (Θ_E) and water (Θ) temperatures.

Also the sampling was made for later chemical analysis in the laboratory and terrestrial photography was taken.

The films were analyzed qualitatively (by photointerpretation) and quantitatively (by microdensitometry).

2. CHARACTERISTICS OF REQUENA DAM.

The Requena Dam is located in Tepeji del Rio, Edo de Hgo. Long. W. $99^{\circ}18'14''$, Lat. N. $19^{\circ}57'40''$ (Figure 1).

This dam is used extensively as the agricultural water supply for the surrounding district (Distrito de Riego 03, Tula, Hgo.). The three most important tributaries of the dam are: South; the Tepeji river, Northeast; the Salto channel, and Northwest; the wastewater channel of Tepeji town.

3. AERIAL PHOTOGRAPHY

The aerial photography was taken on June 11, 1976 by a CESSNA aircraft of the S. R. H. at an altitude of 11 000 feet approximately with a PRAKTICA LTL camera equipped with infrared ektachrome film (35 mm) and #12 (yellow)+ CC50C-2 filters. We were able to obtain photographs from only three sample points: I, II and III (Figures 1 and 2).

4. GROUND - TRUTH PROGRAM.

Remote Sensing needs a ground-truth program support in which it is necessary to measure at the sample points the parameters of interest. The physical variables mentioned above were determined on June 15, 1976 (Table I).

The difference between environmental and water temperatures was from 2 to 6°C. The pH measures were in agreement with the laboratory results (see Table I). The laboratory analysis (made in the Institute of Geology, U. N. A. M.) of the chemical samples reports on the following (Tables I and II): the total solids (which were suspended in the original sample), pH, conductivity (C) and organic matter. The results of the analysis show a similar water composition for the sample points I and II but the sample points III (D. F. wastewater) and IV (at the end of Tepeji river) show a very different composition, as we expected.

On June 15, 1976 the terrestrial photography was taken at the sample points with PRAKTICA LTL cameras simultaneously with sampling.

The following films were used: normal and infrared ektachrome (35 mm) with UV and #12 (yellow)+ CC50C-2 filters respectively.

The terrestrial photography has great meaning in the registration of the sample points and give us a guide for the photointerpretation of the aerial photographs.

5. PHOTOINTERPRETATION.

In both types of infrared photographs we observed various blue tones which were caused by the different reflection from the body of water, as Table III shows. They were associated principally to four types of water with different suspended solids concentration (figure 3).

The presence of a reddish tone observed in some cases is probably associated with the existence of vegetative organic matter in the water of the Dam. The bottom effect was also appreciated.

6. MICRODENSITOMETRY.

The aerial and terrestrial photographs were analyzed in an Ortec Densitometer No. 4310. The scanning line passed through the sample points. The spectrum gives the transmissibility vs distance (see Figures 4 and 5). If we know the position of the sample point for the aerial photographs we can obtain the transmissibility associated. The "mean" $(T_{\max} + T_{\min} / 2)$ of the transmissibility in the terrestrial or ground photograph is representative for the comparison with the respective value of the sample point in the aerial photograph. The table IV shows the transmissibility.

7. RESULTS.

In general terms the results of the photointerpretation, ground-truth program and the microdensitometry agree with each other. The alterations produced by the presence of clouds, spume and the bottom effect were appreciated with the help of the ground or terrestrial photography as shows the Table IV.

The water color in the infrared film coincides with the observations of Sadasivam (1970) for the pH measured.

The Figure 6 shows the transmissibility for pairs of sample points at the same aerial photograph. In the first approximation a relationship between transmissibility and concentration of total suspended solids is suggested. Only in the photograph with solar glitter we see a different behavior (see Figure 6).

For the three sample points mentioned a linear correlation is obtained (Figure 7), in spite of the four days of difference between the aerial photography and the sampling.

Similar relationships were obtained by other authors: (Ruff et al, 1972; Klooster and Scherz, 1974) between turbidity and total suspended solids. Klooster, et al, worked also for the percent of reflectance vs. turbidity and total suspended solids.

The results of this preliminar study have been considered in the preparation of the next stage. In which we will try to get vertical multispectral aerial photography simultaneously with sampling.

For this first work our resources were very limited. Consequently, our study is still incomplete because we need the biological and bacteriological samplings and also the measure of other physical and chemical parameters of interest for the water quality.

ACKNOWLEDGMENTS

We would like to thank the following for their cooperation:

The Remote Sensing Department of the Secretary of Hidraulic Resources (SRH), the Chemical Laboratory of the Institute of Geology (UNAM); G. Izquierdo, F. Uribe and F. Olivares for their help in the sampling; P. Segarra for her patient work in the preparation of this paper and also E. Angeles for the typewriting.

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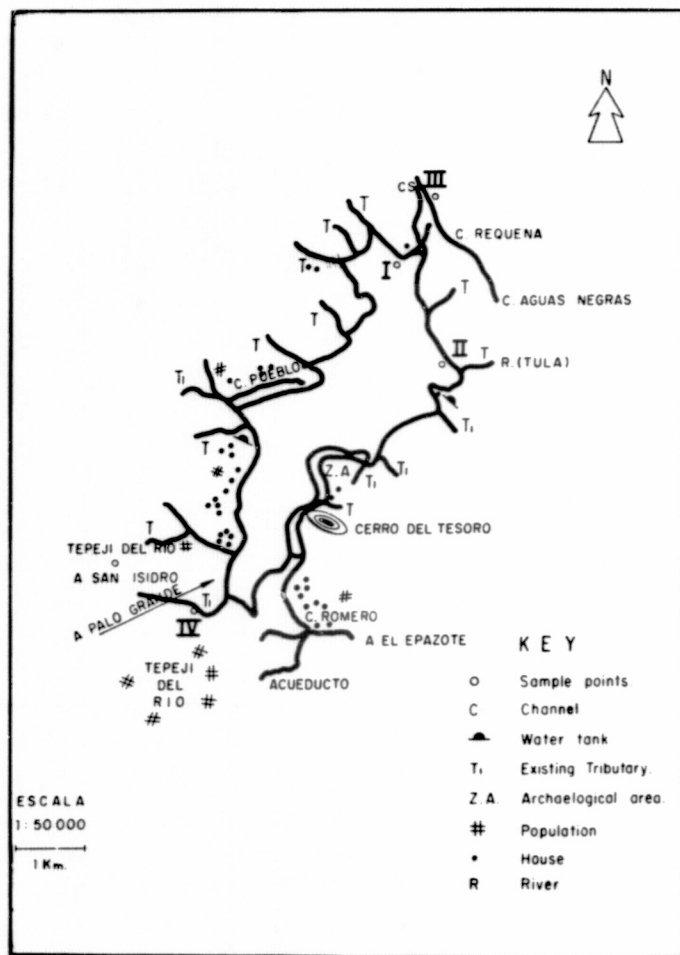


FIGURE 1. THE REQUENA DAM MAP.

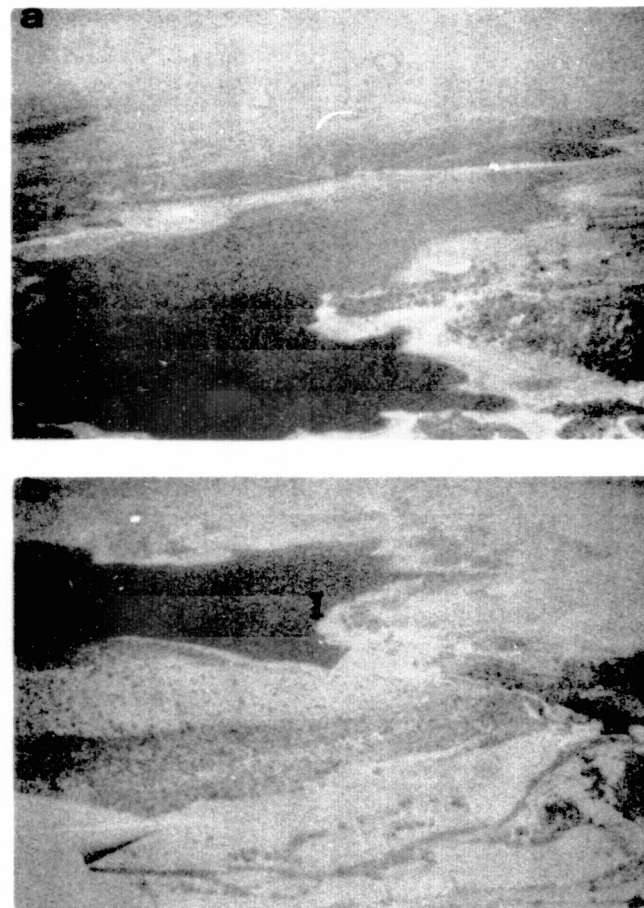
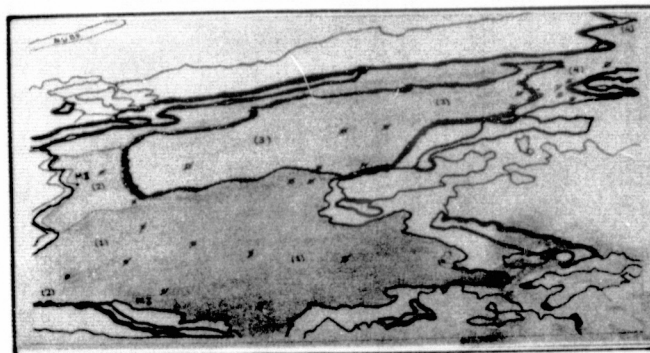


FIGURE 2. AERIAL PHOTOGRAPHS. a) Sample Points I y II. b) Sample Points I and III.

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KEY

- () Suspended Solids concentration 1, 2, 3, 4 (in increasing order)
- o Sample points
- φ Possible existence of organic matter (reddish tone)

FIGURE 3. PHOTOINTERPRETATION MAP OF THE FIGURE 2a.

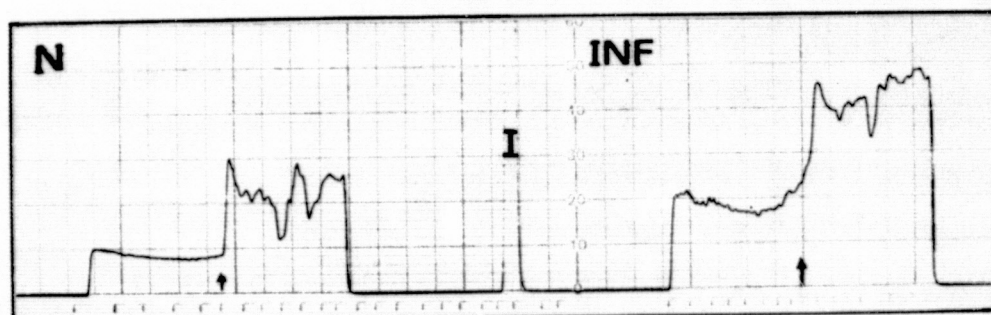


FIGURE 4. TRANSMISSIBILITY OF GROUND PHOTOGRAPHY.
For the sample point I, the spectra of the normal (N) and
infrared (INF) films are shown. The arrow indicates the
limit between water and land.

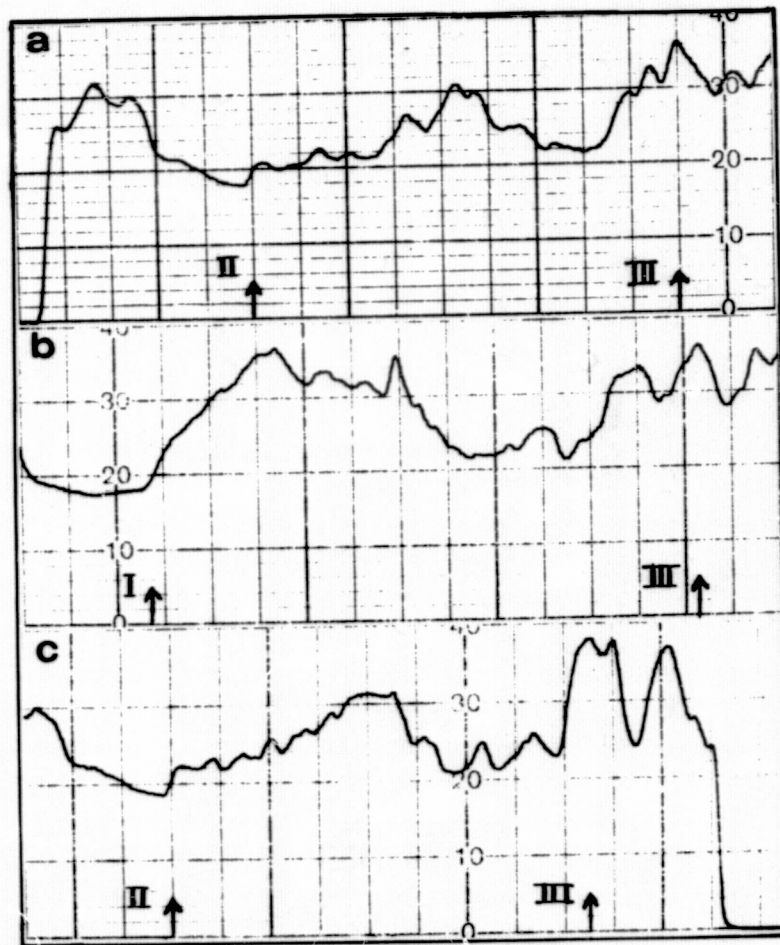


FIGURE 5. TRANSMISSIBILITY OF AERIAL PHOTOGRAPHY. For the same film we have the three scanning lines a, b and c. The arrows show the respective sample points.

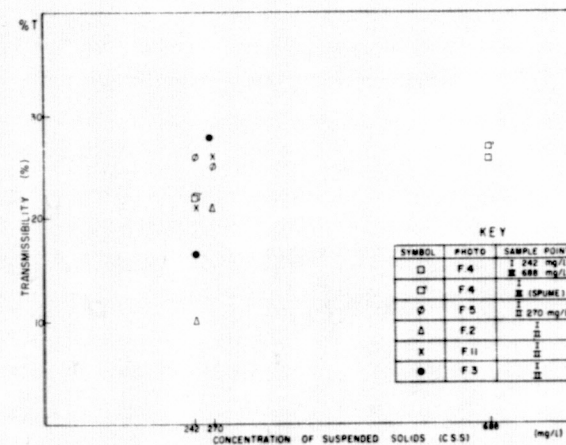


FIGURE 6. RELATIONSHIP BETWEEN TRANSMISSIBILITY AND CONCENTRATION OF SUSPENDED SOLIDS FOR PAIRS OF SAMPLE POINTS. The letters a, b and c indicate two different scanning lines in the same film F.26

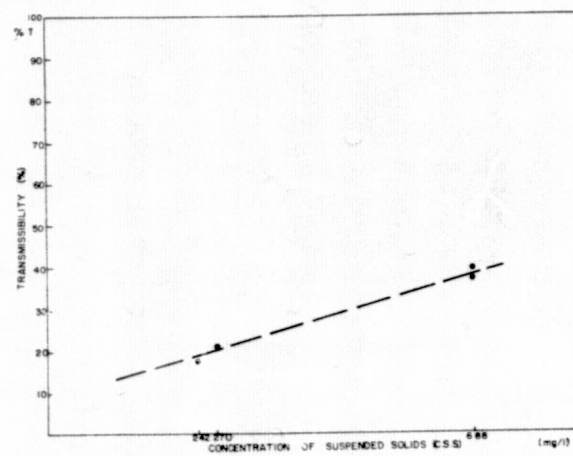


FIGURE 7. LINEAR CORRELATION.

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TABLE I. PHYSICAL PARAMETERS

" IN SITU "				" A POSTERIORI " (CH. A.)		
SAMPLE	θ_E	θ	pH(± 1)	pH	C($\mu\Omega$)	TOTAL SOLIDS (mg/l)
I	26	20	6	7.3	280	242
II	26	24	6	7.0	360	270
III	26	/	/	6.7	810	688
IV	27	23	7	7.1	370	284

CH. A. = CHEMICAL ANALYSIS.

TABLE II. CHEMICAL ANALYSIS

COMPOSITION (mg/l)	SAMPLE				OBSERVATIONS
	I	II	III	IV	
Cl	14.61	14.61	62.08	44.79	EXISTENCE OF ORGANIC MATTER IN THE SAMPLE POINTS I, II AND III.
SO ₄	17.26	14.80	15.62	16.44	
NO ₃	0.88	0.88	0.88	2.20	
CO ₃	0.00	0.00	0.00	0.00	
HCO ₃	175.29	187.27	414.36	131.85	
HPO ₄	traces	0.05	1.00	0.03	
Na	19.00	23.00	105.00	25.50	
K	6.50	5.50	20.00	6.00	
Ca	38.08	30.46	30.46	34.27	
Mg	9.27	13.88	27.76	9.27	
SiO ₂	25.00	29.00	110.00	51.00	

TABLE III. PHOTOINTERPRETATION

SAMPLE	PHOTOGRAPH	OBSERVED TONES	POSSIBLES CAUSES	OBSERVATIONS
I	INF. GROUND	LOADEN BLUE ⁺	C.S.S. 1	POSSIBLE EXISTENCE OF ORGANIC MATTER
	AERIAL			
	NORMAL Gr.	BLUE GREEN-SEA		
II	INF. GROUND	LIGHT BLUE ⁺	C.S.S. 2	POSSIBLE EXISTENCE OF ORGANIC MATTER AND DIFFERENCES IN D.O.
	AERIAL			
	NORMAL Gr.	GRAY		
III	INF. GROUND	VERY LIGHT BLUE ⁺	C.S.S. 3	POSSIBLE:EXISTENCE OF ORGANIC MATTER, DETERGENT AND GREASE.
	AERIAL			
	NORMAL Gr.	GRAY		
IV	GROUND NORMAL	MILKY WHITE		
	INF.	METALLIC BLUE		

+ = REDDISH TONE
C.S.S.= SUSPENDED SOLIDS CONCENTRATION (1,2 and 3; in increasing order)

TABLE IV. MICRODENSITOMETRY (TRANSMISSIBILITY)

SAMPLE	AERIAL PHOTOGRAPHY						GROUND PHOTOGRAPHY		C.S.S. (mg/l)
	F.26	F.4	F.5	F.2	F.11	F. 3	N	INF	
I	18	22	26	10	21	16.5	8	19	242
II	20.5	/	25	21	26	28	20.5	34.5*	270
III	36	26	/	/	/	/	14.2	26	688
III	38	27	/	/	/	/	10	18	688
IV	/	/	/	/	/	/	15	28**	284

F.# =PHOTOGRAPH.
*BOTTOM AND CLOUDS EFFECTS. **CLOUDS EFFECT. 'SPUME EFFECT.

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USE OF MULTISPECTRAL DATA IN DESIGN OF FOREST SAMPLE SURVEYS¹⁾

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ABSTRACT

The use of multispectral data in design of forest sample surveys using a computer software package, WILLIAM, is described. The system allows evaluation of a number of alternative sampling systems and, with appropriate cost data, estimates the implementation cost for each.

1. INTRODUCTION: The Resource Management Context

Remote sensing data sources, including satellite data and conventional aerial photography, as well as direct measurement on the ground are logical inputs for both design and implementation of information production systems to meet management information needs. It is recognized that sampling plays an important role in generating relevant information for managing large geographic populations. The central problem, therefore, is to define the kind and amount of sampling and the place of remote sensing data sources in that sampling system to do the best possible job of meeting the manager's informational needs.

Perhaps the most significant recent event which shows the increasing importance of implementing comprehensive procedures for describing and monitoring wildland systems, is the passage of the Forest and Rangeland Renewable Resources Planning Act (RPA) of 1974 and related legislation such as the Multiple Use-Sustained Yield Act of 1960 and the National Environmental Policy Act. This legislation is directed primarily toward management activities of the US Forest Service, but the implications for other federal and state agencies as well as industrial and non-industrial private lands are present. In particular, the RPA specifies procedures to be followed in developing comprehensive policies and programs with respect to wildland management and requires frequent resource assessments to evaluate progress toward these ends. The necessity to consider all the varied uses and products associated with these lands has shown the need for extensive broadly-based information on a variety of wildland characteristics including forests, range, fish and wildlife, recreation and wilderness, land, and water. It is not at all clear what type of information production procedures will evolve to meet these needs, but the strong implication is that sampling systems will play a significant role and that multiple characteristics will be of interest. With this premise, a systematic procedure for evaluating sampling alternatives, where the objective is to estimate several parameters, is of obvious importance.

A wildland resource system may be partitioned into two interrelated subsystems: the forest ecosystem and the management system, as shown in Figure 1. The ecosystem is the physical entity to be managed and is defined by geographic

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limits. Man's activities and efforts to manipulate and control the ecosystem represent the management system. Both may be viewed as composed of a number of subsystems. In Figure 1, the management system is shown as interacting with the ecosystem primarily through the information system and direct applications of treatments. It is the information system which provides policy-makers and decision-makers with the estimates of current conditions so that informed management decisions may be made and appropriate treatments applied to the ecosystem. Sampling systems are logically implemented within the scope of information systems as primary information production tools. It is this operating framework which must be kept in mind in planning and designing sample survey systems to meet the informational needs of managers.

2. METHOD: Formulation of the Multivariate Survey Planning Model

Given the important role of sampling for resource management and the increasing emphasis on multivariate sampling applications, it is evident that a formal planning mechanism is needed to document and improve the selection of techniques and procedures to be used in meeting estimation objectives. One approach to providing such a mechanism for multivariate survey design is the planning model developed in this study. Aldred (1971) developed a planning model using a population representation derived from a large sample of photo measurements taken over a 25,000 acre test site in Ontario, Canada. The model was not spatially referenced and was limited to a univariate case for estimation of timber volume. In the present application a spatially-referenced population model is derived and multivariate estimation objectives are assumed. The planning Model is formulated as a tool for use in making inferences about how best to sample a particular population to meet specific multivariate information needs. Its objective is to produce an evaluation of alternative sampling systems based on an analysis of spatially-referenced population data.

For this study the population representation is based on satellite multispectral data combined with supplementary information on a set of resource parameters to be estimated by the sample survey. One result of the analysis would be an estimate, or prediction, of the implementation cost for each alternative sampling system. Then, based on estimates for a set of alternatives, inference can be made as to which alternative provides the most cost effective way to sample the population from which the population model was derived.

Two major premises are the basis for the approach used in the planning model. The first is that the population representation, based on satellite and other data, reflects the real-world population with sufficient realism that inferences about alternative sampling systems will be valid for the actual population to be sampled. This hypothesis must go untested since the data required to test it would be impractical to obtain. It is precisely in cases where information is scarce and subject to great uncertainty that sampling is an important tool. Second, the performance measure for alternative systems is the cost of implementing a given alternative system. System cost combined with constraints on system performance, leads to the formulation of a particular model for the allocation of effort. This performance measure, which is actually "minimum cost for informational requirements", is widely used in sample survey design.

Figure 2 shows the major components of the planning model. It consists of a set of FORTRAN computer programs, collectively known as the WILLIAM package, implemented on a CDC 7600 computer. Major inputs, a spatial class assignment file and associated class statistics, as well as output results, specifications for alternatives and a spatially-referenced sampling frame, are also included.

The spatial class assignment file is a map of the population with a class assignment for each element of the map. This file is produced by prior analysis of satellite multispectral data using established discriminant analysis or

classification procedures. In the most common application each element, or cell, in the map is assigned to a particular land use or vegetation type, e.g., water, urban, bare, hardwood forest, conifer forest, etc., based on the spectral data recorded for the cell. Class structure must be consistent with the needs of the manager. Statistics for each class represent a synthesis of other data sources and summarize information for the parameter set to be estimated and include a mean vector and associated covariance matrix.

Program SIMULATE combines the two input files and generates individual parameter values for each element in the population. Simulation is based on an assumed multivariate normal distribution for each class with known mean vector and covariance matrix. The resultant map file contains the class assignment and simulated parameter set for each element in the population.

Program CLUSTER collapses the population representation into sampling units formed as clusters of individual elements. The stratification of sampling units, by assigning clusters to the class with the plurality of elements within the cluster, is accomplished and summary statistics including variance components for each stratum are derived. These statistics depend on a number of specifications which describe the nature of the sampling system to be considered.

Program SUMT uses the summary statistics in an allocation procedure to determine the minimum-cost allocation of sample sizes for a specific sampling strategy and then summarizes system cost and sample sizes (Mylander et al, 1971).

2.1 The Population Representation

The population representation, produced by program SIMULATE, provides the starting point for the planning process. It must preserve the spatial distribution characteristics, a key feature of geographic populations, which may have a significant impact on the sampling methods used. In addition, if the data base has been well designed and maintained, available and pertinent data for the population will be readily available. As was seen in the description of program SIMULATE the generation of a detailed spatially-referenced population model requires two very specific kinds of data inputs: 1) a grid-type geographic data base, with class assignments for each cell; and 2) supporting data which, for class, provides information on the parameters to be estimated.

Most geographic data base structures use either the polygon or grid approach. The first uses a series of polygons, with coordinates of vertices in some convenient system, to code information on location of the data elements. The major advantage is that less data storage space is required, but this is offset by the necessity of using more complicated analysis methods. If the area is partitioned into mutually-exclusive cells, data elements may be assigned to each unit in the population. Size, number and shape of the cells determines how much detail is reflected in the data base. A 40-acre cell size would give a very different representation than a 4-acre size. A major disadvantage of the grid system is that more storage is required since each element in the population must be identified and labeled; however, this is offset by simpler analysis methods. A cell-by-cell class assignment, or stratification, is an excellent tool for evaluating spatial distribution as it influences sampling methods. In this study such a digital data base is available as the result of a discriminant analysis of multispectral data, acquired by satellite. Each cell, roughly one acre in size, is assigned to one class in a land use and vegetation classification scheme. Complementing this partitioning into land uses and vegetation classes are sample data providing estimates of specific parameters of interest for each of the classes.

The supporting data for each land use class may be obtained from special pilot surveys, or from previous in the same area. This information, representing available knowledge of the parameter set to be estimated, combined with

appropriate assumptions about the probability distribution of the variables over the population makes it possible to generate individual cell values by simulation, while preserving average characteristics and spatial distribution influences. This technique is very useful where population sampling units are likely to be clusters of cells rather than individual cells since the variability due to simulation is reduced by clustering. The most obvious distribution for simulation is the multivariate normal, which is easily simulated (Naylor, et al., 1966). Others derived from the multivariate normal, including the multivariate chi-squared and Student's *t* distribution could be simulated to account for some types of departures from normal. With a cell-by-cell population representation, summaries are easily made to obtain variance components required for the sampling alternatives to be evaluated.

2.2 Allocation of Effort

Answering the questions, How to sample? and at what cost?, are the goals of the allocation of effort component. It requires population summary statistics as input and produces, for a given alternative sampling system, the optimum sample sizes and allocations as well as the implementation cost. To achieve this goal requires, more specifically, 1) mathematical representations of variance relationships and sampling costs, 2) estimates for cost coefficients, 3) estimates of population variability, and 4) a method for finding the least cost allocation of sampling resources.

If mathematical models for the cost and variance relationships can be obtained for particular sampling schemes, mathematical programming provides a method for allocating sampling resources. The mathematical programming problem is formulated in general terms as: minimize the objective function subject to a set of constraint functions (Fiacco and McCormick, 1968; Hillier and Lieberman, 1967). Special cases of the formulation are obtained depending on restrictions on the form of the objective and constraint functions. For the planning model formulation the objective function is a cost function and the constraints are variance functions for each parameter. Since these functions are generally not linear, linear programming is not appropriate. However, the class of problems encountered in allocating sampling effort conform to the assumptions of the convex nonlinear programming problem, and for this problem general and unique solutions have been shown to exist (Fiacco and McCormick, 1968). With the solutions to the allocation problem it is possible to identify the optimum sampling design (among the alternatives considered) while still meeting the constraints imposed.

In summary, the planning model utilizes a population representation which is derived from the data base of the information system and it incorporates as much of the basic data as is possible including simulation of certain detailed values on a unit-by-unit basis. This representation then forms the basis for generating specific inputs to an allocation model, a convex nonlinear programming problem formulated for a specific sampling system. The resulting allocation of effort minimizes the associated cost function. With these basic elements, the scope of the model is limited only by the alternative systems which can be formulated for allocation and by the details of cost or other comparisons which are possible among alternatives.

3. RESULTS: The Quincy Ranger District Study

3.1 Data Inputs

As a result of a 1974 survey for the entire Plumas National Forest, conducted utilizing Landsat multispectral data, large-scale photography, and ground measurements (Titus et al, 1975) a data base of the type required for the planning model was available. The gridded data base structure generated by the

Landsat multispectral scanner system (NASA, 1971) was used in the population model. All other data sources were transformed to the Landsat base. This base is made up of a set of picture elements (pixels) which contain a vector of specific observations made by the scanner at a particular point in time. The on-the-ground area covered by each pixel varies according to parameters associated with the satellite orbit and its relationship to the area scanned. For the Plumas NF it has determined empirically that the area represented by each pixel is a little more than one acre. Individual cells are referenced by an (x,y) coordinate where each point is one pixel. To identify the study area explicitly and to delete all internal blocks of private ownership, an ownership base map was digitized into a local (x,y) coordinate system. This local system was then transformed to the Landsat system using mathematical functions based on least squares regression analysis of a set of control points located in both coordinate systems.

With the source data and study area combined, a maximum likelihood discriminant analysis was performed to assign each pixel in the population to a vegetative or land-use class according to a structure determined by the training areas. As required by discriminant analysis, training areas or examples of particular classes of vegetation and land use are required on which to base the rules for assignment of individuals to specific classes. For the study area two separate analyses were made, because the study area was covered by portions of two Landsat data files, each with 50 to 60 examples of various vegetation and land use categories. Further aggregation of vegetation classes into 17 broad vegetation classes was made by interpreting each of the training areas in light of the desired stratification scheme which included three classes of vegetation (mixed conifer, east-side pine, and true fir) and within each vegetation class, five classes of vegetation conditions (regeneration, immature, mature, over-mature, and poorly stocked) were recognized. Two other classes were specified, hardwoods and a residual of all other classes.

Associated with each of the classes are a number of variables important for management. Depending on the particular ecosystem component to be managed the set could be limited to a few major variables. For example, the 1974 inventory concentrated on variables important for timber management, and therefore, many variables useful in managing such components as recreation, watershed, wildlife, or range were not included. Still, a basic approach to a number of resource values depends on the condition and distribution of the vegetation components. For this reason it is considered appropriate to use as parameters, in the verification and application of the planning model, three characteristics which describe the "tree component" of vegetation. The three are number of trees, basal area, and basal area growth. The last two are highly correlated with the volume and volume growth. At the same time they are basic physical measures of the vegetation component which could be related to other management needs. Number of trees combined with total basal area gives an indication of the relative size of the trees. The sample data from the 1974 inventory provided estimates of the mean vector and covariance matrix for each vegetation class.

Selection of these parameters is not to imply in any way that the planning model is limited to timber related parameters. If data is available any parameter set could be used.

In addition to the cell-by-cell vegetation class assignment and their parameter estimates by class, other data inputs are required including 1) required precision levels, 2) cost components of the sampling activities, and 3) correlation between measurements taken on photographs and on the ground. Alternative values for inputs listed above can be used to evaluate sensitivity of the model to input parameters.

With the population model specified it is possible to evaluate the sampling effort required to meet desired precision levels for each of a number of alternative sampling systems. It is obvious that time and money constraints on the planning phase, as well as the limitations of the planning model, will limit the total number of alternatives which might be evaluated. Nonetheless, by careful selection of the few alternatives to be examined, it is possible to gain valuable insights about the best way to allocate sampling resources in situations where we must act on the basis of incomplete and uncertain information.

Analysis of sampling systems for the Quincy Ranger District was based on alternatives obtained as specific combinations of the following factors: 1) level of confidence and precision, 2) cost components, 3) sampling strategy (single stage, two stage, or two stage with double sampling), 4) selection probability, 5) cluster size, and 6) correlation between measurement variables.

3.2 Results

The only conclusion which holds over all levels of factors examined here is that probability Proportional to size (PPS) sampling requires a lower cost than equal probability sampling, and that a "large" primary sampling unit (PSU) is better with PPS sampling while a small PSU size is better with equal probability sampling. These conclusions must be qualified by the limits of this particular population model and the range of PSU sizes evaluated. However, the implication seems to be that regardless of relationships among the variables themselves, the larger PSU sizes strengthen the relationship between the size variable used for the selection probability and the magnitude of parameter totals by PSU. Conclusions about which alternative system is the best must be qualified by the particular factors and levels which are tested.

To complete the planning process and select the optimum system from among the alternatives requires specifications for sampling system performance in addition to inputs which define the population model and sampling system characteristics. For example, if the system performance constraint were to achieve estimates with allowable errors of **+ 10 percent with probability level** at 95 percent for each parameter, the optimum survey alternative would be estimated to cost \$23,190 and its basic elements would be 1) PSU size of 60 x 6 pixels, 2) selection probabilities proportional to PSU size, and 3) stratified two stage with double sampling. This alternative would be optimal with respect to the planning model which makes a number of specific assumptions about the population characteristics and cost of implementing various sampling alternatives. For this reason there is always a certain element of uncertainty with respect to whether the alternative selected is optimal with respect to the real world population. Preparation of an implementation plan, outlining in detail the operational aspects of the system, would complete the planning process.

Additional details on the results of this application of the planning model, as well as the background for the model development, are provided by Colwell and Titus (1976) and Titus (1977).

4. CONCLUSION

The planning model developed here represents a formalization of the interrelationships which must be considered in planning sample surveys for multivariate applications. As with any model, assumptions are required in order to simplify the "real world" complexities so that a workable model can be formulated. But even with assumptions, some of which require additional research to evaluate their importance, the planning model provides an important mechanism for evaluating the various factors, data and components of a sample survey system. Without this formal planning mechanism, survey design is largely

relegated to experience, hunches and guesses. This is especially true when large multi-purpose surveys are contemplated.

A significant requirement for the successful implementation of a planning model of this kind is the availability, in a useable form, of considerable prior information about the population to be surveyed. A "data base management system", is probably the only way to insure that this kind of information is accumulated and maintained over time. If this level of information is available and its quality is improved as time passes (and more data are acquired), the planning effort becomes more effective and the efficiency of the sampling effort should increase. The Landsat population model used in the Quincy Ranger District study meets this requirement and represents a unique application of a remote sensing data source to planning for sample surveys.

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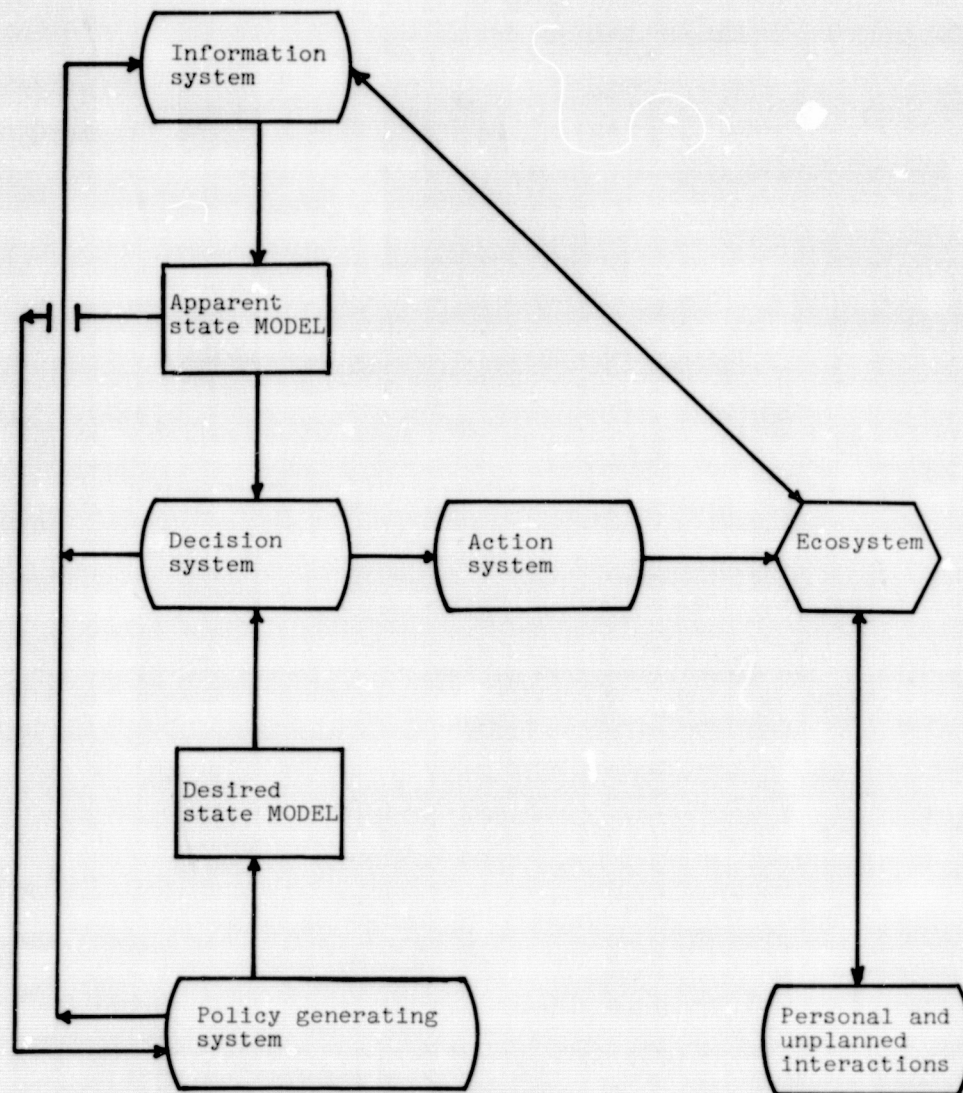


FIGURE 1. MANAGEMENT SYSTEM and the object of management, the ecosystem.

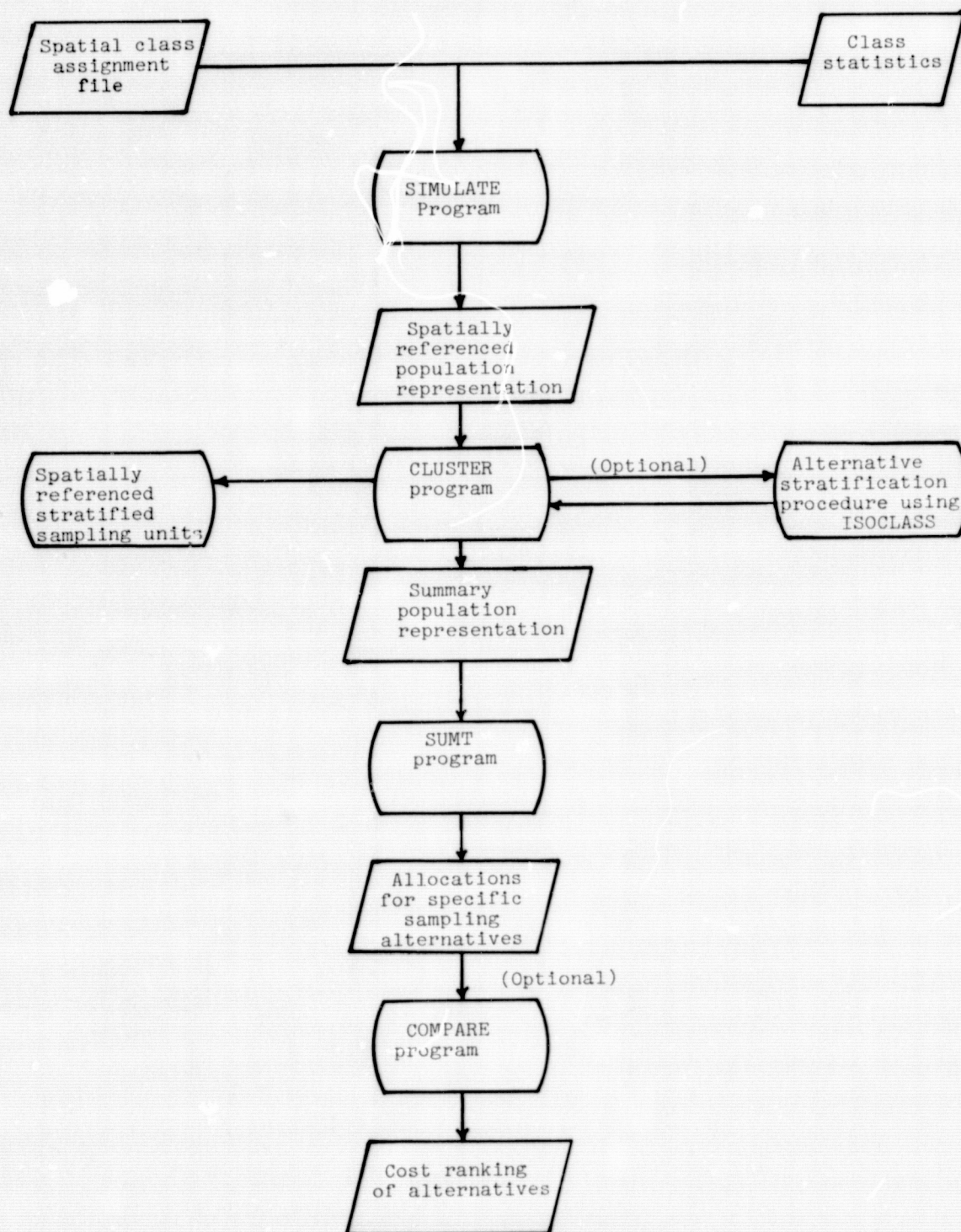


FIGURE 2. The WILLIAM Package, Software System Components

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MONITORING IRRIGATED LAND ACREAGE USING

LANDSAT IMAGERY: AN APPLICATION EXAMPLE

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ABSTRACT

A demonstration of the utility of Landsat imagery for quickly and cheaply estimating irrigated land area was conducted in the Klamath River basin of Oregon. Landsat color composite images, at 1:250,000 scale and acquired on two dates during the 1975 growing season, were interpreted. Irrigated lands were delineated manually, and the irrigated area was estimated, based on dot-grid sampling of the manually delineated lands. The image interpretation estimate of irrigated area was then adjusted by a comparison of interpretation results with ground data on 45 sample plots, each 2.6 square kilometers in size.

Two interpreters independently estimated the irrigated area. Their adjusted estimates were 115,000 hectares and 108,000 hectares respectively, with corresponding 95 percent confidence intervals of $\pm 7,880$ hectares and $\pm 14,000$ hectares. The estimated cost of the survey, exclusive of management costs and training, was \$1,500.

INTRODUCTION

Due to an agreement between the States of Oregon and California regarding the allocation of the water of the Klamath River^{1/}, the Oregon Water Resources Department (OWRD) must periodically estimate the area of irrigated land in the Klamath River basin of Oregon to ascertain how closely the State is approaching the limit stipulated in that agreement. When the irrigated area approaches the limit, a very detailed survey will be needed; at that time the State will impose appropriate controls on the increase of irrigation in the basin. Prior to the advent of repetitive Earth observations from space, no quick and inexpensive method was known for making rough annual estimates of irrigated land in areas as large as the Klamath River drainage (approximately 14,800 square kilometers).

In response to this need, the EROS Data Center (EDC), and the OWRD, carried out a project to demonstrate the feasibility of estimating irrigated land area using Landsat images. This work was performed as a part of the Pacific Northwest Regional Commission Land Resources Inventory Demonstration Project.

The objectives of the project were to demonstrate the methodology, to determine the time and costs required to make an estimate of total irrigated acres in the Oregon portion of the Klamath River drainage, and to ascertain the accuracy that could be achieved. The techniques used were those which could be reasonably undertaken by the OWRD at the present time, and which could be repeated at 1- or 2-year intervals. Thus, the project was designed to demonstrate the application of existing techniques to a resource management problem, rather than to develop new techniques.

^{1/} Klamath River Basin Compact, between the States of Oregon and California. Effective September 11, 1957. Chapter 142, Oregon State Laws, 1957; Chapter 113, California Statutes, 1957.

METHODOLOGY

Problem Definition

It was first necessary to define accurately the type of information required by the OWRD. This was accomplished through a number of meetings of EDC, NASA, and OWRD representatives. It was concluded that at the present time a rough estimate of the total acreage of irrigated land in the Klamath River drainage, repeated every 1 to 5 years, would suffice. Accurate mapping of the lands is not necessary. It was agreed that a method using manual interpretation techniques would be best, in that it would more likely be adopted on an operational basis (providing it was judged to be sufficiently cheap and accurate) by the OWRD. The objectives of the project did not include an exhaustive testing and comparison of all possible methods, but rather a demonstration of the method that was deemed most likely to prove successful.

The chosen method consisted of an interpretation of 1:250,000-scale Landsat color composite images, with the area estimation based on dot-grid sampling of manually delineated agricultural lands. The area estimate was then adjusted through a comparison of interpretation results with ground data on selected sample plots, using a ratio estimation procedure.

Imagery Selection

Landsat imagery used in the interpretation consisted of four 1:250,000-scale color composite prints acquired during the 1975 growing season. It was felt, based on OWRD knowledge of the cropping practices and crop condition change through the growing season, that both a mid-summer and late-summer image would be necessary to discriminate definitively between irrigated and dry-farmed land. A search of all 1975 images led to the selection of those acquired on July 21 and September 4. On each date, portions of two Landsat scenes were needed to cover the entire study area, thus requiring a total of four images. In July all irrigated fields are red on the color composite, but a few nonirrigated fields are also still red. By September, all of the dry-farmed fields are dry, and hence tan in color on the image, while the vast majority of the irrigated fields are still red. Thus, by comparing the two dates of imagery, the interpreter could identify irrigated fields more accurately than with any one single date of imagery.

On July 31, 1975, the NASA U-2 aircraft acquired color infrared photographs at a scale of approximately 1:120,000 of the Klamath River basin. These photographs were used by the field crew as aids in locating plots and plotting the area of irrigated lands within the sample plots. The aircraft photos were not used for the overall interpretation because they could not be expected to be available on a repetitive annual basis as are Landsat images. Furthermore, it was assumed that for most areas to which this estimation approach might be applied, some kind of air photo coverage would be available (U-2 photos are not specifically required).

Sample Plot Selection

Prior to the interpretation of irrigated lands, all agricultural land within the Klamath River basin was delineated on overlays of the Landsat images. This was performed by OWRD personnel familiar with the region. An effort was made to ensure that all irrigated or potentially irrigated land was included within the delineated area. The agricultural land thus delineated was then assigned to one of eight strata representing various types of agricultural land in the region. The description of the strata and assignment of land into strata were based on experience and knowledge of OWRD personnel. The strata were as follows:

<u>Stratum</u>	<u>Description</u>	<u>Average field size</u>
1	low elevation, diverse, poorly drained	16 ha
2	low elevation, diverse, generally well drained	16 ha
3	medium elevation, hay and pasture, well drained	16 ha
4	marshland, use on marsh edges	irregular
5	medium elevation, pasture, poorly drained	260 ha
6	reclaimed swamp or marsh	40 ha
7	high elevation, meadow, and hayland	irregular
8	confined basin, agriculture on areas from which lake has receded	irregular

Sample plots were assigned to strata on the basis of a subjective evaluation of the relative size and diversity of the strata, whereby the largest and/or more diverse strata received the most plots, acknowledging the fact that there may be a bias in the estimates due to disproportionality. The total number of plots was based primarily on an estimate of the number that could be reached by a ground crew during the time allotted for field work on the project.

<u>Stratum</u>	<u>No. sample plots</u>	<u>Approximate total area of stratum</u>
1	3	145 km ²
2	6	580 km ²
3	9	787 km ²
4	7	559 km ²
5	4	207 km ²
6	4	186 km ²
7	10	269 km ²
8	2	42 km ²
Total		45

Each sample plot was randomly selected. This was accomplished by superimposing a rectangular grid over a stratum overlay and selecting grid intersection points using random number tables until the required number in each stratum was obtained. These points were numbered by stratum and transferred to both the Landsat imagery overlays and the U-2 color infrared photos. On the aerial photos, a plot approximately 2.6 km² in size was constructed around each point. The boundaries of each plot were then transferred to the Landsat strata overlay using an optical transfer device.

Ground Data Collection

Each sampling plot was visited in the field by OWRD personnel during the summer of 1975. A map was prepared by the field crew delineating growing season. Using these maps and the aerial photos, the ground crew estimated the percentage of the area of each plot that was irrigated.

Image Interpretation

The interpretation of the Landsat images was performed by two interpreters, independent of each other. One of the interpreters (interpreter A) was quite familiar with the study area, and had collected most of the ground data, while the other (interpreter B), was unfamiliar with the area. The intention was not to statistically compare the performances of the two interpreters, but only to obtain some indication of the effects of familiarity on interpretation accuracy.

The estimation of irrigated land on the Landsat imagery was done stratum by stratum. A random dot grid was laid over the July Landsat color composite images and the strata sample plot overlay. Each dot represented approximately 10.3 hectares^{2/}. The interpreter counted the dots that appeared to fall on the irrigated land, and accumulated his count by strata. Although the bulk of the interpretation was done on the July images, the interpreters referred to the September images to aid their interpretation. Only that area within the initial agricultural land delineations was interpreted, and only dots falling on presumed irrigated land were tallied.

In addition to the overall stratum tally, a separate record was kept of interpretation results for each sample plot. Both the total number of dots in each plot and dots on irrigated land within the plots were tallied, and percent irrigated land was calculated for each plot.

One stratum in which the interpreters encountered some difficulty was in stratum 4, the marshland areas. In some cases it was difficult to differentiate between lush irrigated fields and the naturally subirrigated marshland areas. Although in this instance the interpreters did correctly identify irrigated land, they both felt that this was probably due to their prior knowledge of the area, and not due strictly to a reliance on image parameters. Thus, in the future it might be better to survey marshlands separately, using satellite photos together with intensive ground checks.

Statistical Compilation

Following the computation of ground estimates and interpretation estimates of irrigated area for each sample plot and interpretation estimates for each stratum, an adjusted acreage estimate for each stratum was computed, and the sampling error of that estimate was calculated.

The original interpretation results were adjusted by means of a ratio estimation procedure. For each stratum, the ratio of the average ground estimate of percent irrigation on the sample plots to the average interpretation estimate of percent irrigated land on the plots was calculated. The original dot count for the entire stratum when multiplied by this adjustment ratio, equals the adjusted dot count for the stratum. The interpretation estimate is thus corrected, based on the ratio of ground estimate to interpretation estimate for the sample plots. The corrected dot count for each stratum was then converted to acreage by multiplying by 10.3 hectares per dot. The basin total is a sum of the stratum totals. The interpretation dot counts, as well as the corrected counts and area figures are given in Table I.

As shown in Table I, the final adjusted acreage estimates of irrigated land in the study area were 115,000 hectares and 108,000 hectares by interpreters A and B respectively.

The sampling error of the estimate was calculated for each stratum independently. These were then combined to obtain the sampling error and confidence limits for the entire area.

^{2/} Actually, the scale on the Landsat prints varied somewhat from image to image and from place to place on the same image. However, the average scale of the images was approximately 1 cm = 2.5 km which corresponded to a dot equivalent to 10.3 hectares.

DISCUSSION OF RESULTS

The estimates made by the two interpreters of the irrigated acreage in the Klamath River basin differ by 7,300 hectares, or approximately 6 percent. Considering the rather inexact techniques used, this agreement is quite encouraging. The only stratum in which their adjusted acreage estimates differed greatly was stratum 7. This was to be expected, however, as that stratum presented by far the greatest interpretation problems due to small and irregular fields and the presence of subirrigated areas (fields which remained green through the growing season due to available natural ground water).

In general, interpreter A tended to overestimate irrigated acreage in the sample plots, and hence his adjustment ratios were less than 1.0, whereas the opposite was true for interpreter B. Thus, there was considerable difference between their overall counts before adjustment, but the difference was reduced by the adjustment process. Nevertheless, the adjustment ratios for all the major strata were between .90 and 1.04, indicating a reasonably accurate interpretation of the sample plots by both interpreters.

The overall estimates, however, are of little use in evaluating the precision of the estimation process. This can only be done through an evaluation of the agreement between interpretation and ground data estimates on the sample plots as expressed by the sampling error and confidence limits, which are shown in Table II. The statistics used in computing these figures are described in the Appendix.

The stratum sampling errors for interpreter A were considerably lower, in general, than those of interpreter B (low sampling errors are desirable). The individual stratum sampling errors are combined to give overall estimate sampling errors. Thus, interpreter A had a much lower overall sampling error (3.8 percent) than did interpreter B (7.2 percent), although both can be considered good for interpretation methods used. That interpreter A was familiar with the test area, and had collected ground data on the sample plots, probably explains his superior performance.

As confidence limits are a direct function of the standard error as is sampling error, here again interpreter A had a better performance than interpreter B. The 95 percent confidence limits can be interpreted as: unless a chance occurrence with a probability of 5 percent had occurred, the interval specified contains the true value. Thus there is a high probability (95 percent) that, based on the work of interpreter A, the actual irrigated land acreage is between 107,000 hectares and 123,000 hectares.

Upon completion of the survey, the results were submitted to OWRD for evaluation. Their statement regarding the survey is "the PI (photo interpretation) of irrigated lands in the Klamath Basin provided a quick, economical method of estimating total irrigated lands. We recognize that the method is perhaps the least refined of the methods available at current technological levels. We also believe that the PI is adequate for the purpose for which it was intended, namely to give a gross estimation of the total irrigated area. The stratification of irrigated areas into eight classifications served to identify some PI problems, especially the marshland strata. While a statistical level of accuracy can be computed, the actual accuracy as measured against a measured standard is not yet available. The standard will be available upon completion of the upcoming Klamath Basin adjudication survey. In summary, we believe the PI, as demonstrated is a useful, economical and quick method of accomplishing a reasonable estimate of the number of acres irrigated in the Klamath Basin in 1975. We also believe that a repetition of this procedure would serve to monitor the irrigated development in the basin."

The costs of conducting the survey as estimated by OWRD, exclusive of management and training were:

Ground data collection

Salary of field personnel, 65 hours	\$ 365
Mileage, 1,206 miles at 14¢/mile	169
Miscellaneous expense	17

Photo interpretation

Salaries of two interpreters, 84 hours	471
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Imagery costs

Four Landsat color prints, scale 1:250,000 at \$40	160
Twenty color aerial photos, scale 1:120,000 at \$12	240
	<u>\$1,422</u>

In addition, an estimate was made by OWRD as to the costs of inventorying irrigated acreage with 95 percent accuracy using conventional methods. These were:

Low-altitude aerial photos, 300 at \$4.00 (used for plotting ground data)	\$ 1,200
Salaries - 2-man crew - ground data	3,747
Per diem - 2-man crew - ground data	5,416
Mileage - 2-man crew - ground data	1,170
Draftsman - making map and computing acreage	8,540
	<u>\$20,073</u>

The results reported here are encouraging in that the sample errors are quite low given the relatively unsophisticated interpretation methods used. Certainly the results could be improved, but only by expending considerably more time and money. Thus, it is reasonable to speculate whether a small improvement in accuracy would be worth the additional expenditure. The results should, however, be evaluated with some reservation. There is no way to ascertain exactly how correct the interpretation estimates are, short of ground data collection for the entire data. We can, however, make a probability statement in the form of the calculated confidence limits.

A selected methodology has been demonstrated which yields an acreage estimate and a statement about the expected reliability of that estimate. It is a simple and inexpensive methodology requiring no sophisticated equipment except that needed to produce the Landsat imagery. The size and number of sample plots and their number were selected somewhat arbitrarily, and changes might yield significantly different results. Nevertheless, given the costs and accuracies discussed here, there does exist a basis for evaluating the demonstrated method on its own merits.

APPENDIX

Computation of Sampling Error and Confidence Limits: Detailed Description

I. Individual stratum computations

n_j = number of sample plots in j^{th} stratum

N_j = total possible number of sample plots in j^{th} stratum

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x_{1j} = interpretation estimate (in percent) of i^{th} plot in j^{th} stratum

y_{1j} = ground estimate (in percent) of i^{th} plot in j^{th} stratum

$\hat{R}_j$ = adjustment ratio for j^{th} stratum

$S\bar{y}_j$ = estimated standard deviation of the mean for j^{th} stratum

$\hat{A}_j$ = estimated mean percent irrigated land per 640 acre (258.6 ha) sampling plot in j^{th} stratum

SE_j = sampling error of the mean for j^{th} stratum

$$SE_j = \frac{S\bar{y}_j}{\hat{A}_j} \times 100 \text{ where:}$$

$\hat{A}_j$ = $\frac{\text{irrigated land interpretation estimate (unadjusted) in } j^{th} \text{ stratum}}{\text{total land area in } j^{th} \text{ stratum}} \times 100$, and

$$S\bar{y}_j = \sqrt{\frac{S^2 y_j + \hat{R}_j S^2 x_j - 2\hat{R}_j S x_j y_j}{n_j} \left(1 - \frac{n_j}{N_j}\right)} \text{ where:}$$

$$S^2 y_j = \frac{\sum_{i=1}^{n_j} y_{1j}^2 - \frac{(\sum_{i=1}^{n_j} y_{1j})^2}{n_j}}{n_j - 1}, \quad S^2 x_j = \frac{\sum_{i=1}^{n_j} x_{1j}^2 - \frac{(\sum_{i=1}^{n_j} x_{1j})^2}{n_j}}{n_j - 1}, \text{ and}$$

$$S x_j y_j = \frac{\sum_{i=1}^{n_j} x_{1j} y_{1j} - \frac{(\sum_{i=1}^{n_j} x_{1j})(\sum_{i=1}^{n_j} y_{1j})}{n_j}}{n_j - 1}$$

The values used in the calculations and results for this investigation are shown in Table III.

II. Total area computations

Due to the fact that all sample plots in stratum 4 were devoid of irrigated land except one, which was 100 percent irrigated, and that in each case the plots in stratum 4 were perfectly interpreted by both interpreters, the data for that stratum do not lend themselves to a meaningful computation of sampling error (it is, in effect, zero). Thus all computations for the entire watershed shown below exclude stratum 4 data.

N_T = total possible number of sample plots in test area (see Table III)

$S\bar{y}_T$ = estimated total area standard deviation of the mean (from weighted stratum variances)

$\hat{A}_T$ = estimated mean percent irrigated land per 640 acre (258.6 ha) sample unit in test area

$SE_T = \frac{S\bar{y}_T}{\hat{A}_T} \times 100$ = sampling error of the mean for entire test area, where:

$\hat{A}_T = \frac{\text{irrigated land interpretation estimate (unadjusted) for entire test area}}{\text{total land area in entire test area}} \times 100$, and

$$S\bar{y}_T = \sqrt{\frac{1}{N_T^2} \sum_j \left[\frac{N_j^2 S^2 y_j}{n_j} \left(1 - \frac{n_j}{N_j} \right) \right]}, \text{ where}$$

$$S^2 y_j = S^2 y_j + \hat{R}_j^2 S^2 x_j - \hat{S}R_j S x_j y_j$$

Variance and sampling error values obtained in this investigation are as follows:

	Interpreter A	Interpreter B
$S\bar{y}_T$ (in %)	1.82	3.17
$\hat{A}_T$ (in %)	47.3	44.3
SE_T (in %)	3.8	7.2

III. Confidence Limits

Confidence limits were obtained by converting the percent irrigated land values to acreage assuming 640 acres per sample plot and a total of 856 possible sample plots in the entire area (excluding stratum 4). Hence:

$$\hat{A}_T \text{ (in acres)} = \hat{A}_T \text{ (in \%)} \times 856 \text{ plots} \times 640 \text{ acres/plot}$$

and

$$S\bar{y}_T \text{ (in acres)} = S\bar{y}_T \text{ (in \%)} \times 856 \text{ plots} \times 640 \text{ acres/plot}$$

The results of the confidence limit computations for this investigation are shown below.

$$95\% \text{ confidence limits} = \hat{A}_T \pm 1.96 S\bar{y}_T$$

	Interpreter A	Interpreter B
$\hat{A}_T$ (in hectares, excluding stratum 4)	105,000	97,800
$\hat{A}_T$ (in hectares including stratum 4)	115,000	108,000
$S\bar{y}_T$ (in hectares)	4,028	7,016
$1.96 S\bar{y}_T$ (in hectares)	7,880	14,000
Upper limit (in hectares including stratum 4)	123,000	122,000
Lower limit (in hectares including stratum 4)	107,000	94,000

Table I
INTERPRETATION RESULTS AND ADJUSTED IRRIGATED
LAND ESTIMATES, BY STRATUM

Interpreter A				
Stratum	Raw dot count	Adjustment ratio	Adjusted dot count	Adjusted area (ha)
1	941	.98	920	9,700
2	3,469	.93	3,200	33,000
3	3,103	.93	2,900	30,000
4	1,032	1.00	1,000	11,000
5	1,626	.90	1,500	15,000
6	1,365	.90	1,200	13,000
7	581	.66	380	3,900
8	18	.72	13	130
Total	12,135		11,013	115,000
Interpreter B				
1	971	1.04	1,010	10,400
2	3,008	1.04	3,130	32,400
3	2,513	1.04	2,610	27,000
4	987	1.00	987	10,200
5	1,424	1.00	1,420	14,700
6	1,167	.96	1,100	11,000
7	196	.89	170	1,800
8	24	.54	13	130
Total	10,290		10,440	108,000

Table II
PRECISION ESTIMATION STATISTICS

	Interpreter A	Interpreter B
Stratum Sampling Errors (%) Stratum 1	1.76	1.5
Stratum 2	5.28	6.4
Stratum 3	10.6	22.2
Stratum 4	0	0
Stratum 5	5.2	7.9
Stratum 6	11.7	22.0
Stratum 7	18.4	59.6
Stratum 8	2.3	105.2
Overall Estimate Sampling Error (%)	3.8	7.2
95% Confidence Interval (ha)	+7,880	+14,000
95% Confidence Limit, Upper (ha)	123,000	122,000
95% Confidence Limit, Lower (ha)	107,000	94,000

Table III
VALUES USED IN CALCULATION OF SAMPLING ERROR

Interpreter A						
Stratum	n_j	N_j	$\hat{R}_j$	$S\bar{y}_j$ (%)	$\hat{A}_j$ (%)	SE_j (%)
1	3	56	.98	1.16	65.8	1.76
2	6	224	.93	3.04	57.6	5.28
3	9	304	.93	4.00	37.9	10.6
4	7	216	1.00	0	19.1	0
5	4	80	.90	3.80	73.2	5.2
6	4	72	.90	7.98	68.2	11.7
7	10	104	.66	2.70	14.7	18.4
8	2	10	.72	.075	3.25	2.3
Total	45	1066				
Total excluding Stratum 4	38	850				

Interpreter B						
1	3	56	1.04	1.11	72.1	1.5
2	6	224	1.04	3.57	55.9	6.4
3	9	304	1.04	7.62	34.3	22.2
4	7	216	1.00	0	18.3	0
5	4	80	1.00	5.60	71.2	7.9
6	4	72	.96	13.77	62.2	22.0
7	10	104	.89	3.99	6.7	59.6
8	2	16	.54	3.47	3.3	105.2
Total	45	1066				
Total excluding Stratum 4	38	850				

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INFLUENCE OF GROUND LEVEL SO₂ ON THE DIFFUSE TO
DIRECT IRRADIANCE RATIO IN THE MIDDLE ULTRAVIOLET

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ABSTRACT

We examine the dependence of the ratio of the diffuse to direct irradiances at the ground for a wavelength of 315.1 nm and propose a passive remote sensing method based on ratio measurements for obtaining the optical thickness of SO₂ in the vertical column. If, in addition to the ratio measurements, the SO₂ density at the ground is determined using an appropriate point-sampling technique then some inference on the vertical extent of SO₂ can be drawn. We present an analytic representation of the ratio for a wide range of SO₂ and aerosol optical thicknesses and solar zenith angles which can be inverted algebraically to give the SO₂ optical thickness in terms of the measured ratio, aerosol optical thickness and solar zenith angle.

1. INTRODUCTION

The ratio of the diffuse to direct irradiance transmitted by the atmosphere and measured at the ground is sensitive to absorbing species in the troposphere due to the concentration of scattering species there. Klenk, McPeters and Green (1977) have used the diffuse to direct ratio at 305.5 nm to infer the tropospheric ozone density. Below 300 nm ratio measurements are difficult to make due to the extremely weak signals involved. Green and Klenk (1977) point out that when diffuse to direct ratio measurements are coupled with point-sampling of the ground-level ozone density that some inference can be made as to the altitude profile through the determination of the scale-height parameter of a realistic profile function.

2. RATIO SENSITIVITY TO SO₂

The absorption coefficient of SO₂ like that of O₃ decreases rapidly as the wavelength increases beyond 290 nm. Throughout the 290 to 320 region the SO₂ absorption coefficient is larger than the ozone coefficient. In this paper we will study the sensitivity of the ratio at 315.1 nm to SO₂ in the atmosphere. There are two important reasons why remote sensing of SO₂ would be more practical near 315 nm than at smaller wavelengths. Firstly, the SO₂ absorption coefficient is 8.5 times larger at 315 nm than the ozone absorption coefficient. Secondly, ratio measurements are more easily and more accurately made at 315 nm due to the greater atmospheric transmissivity.

We will assume that the sulfur dioxide is well mixed to an altitude which we will call the SO₂ mixing height and that above this the SO₂ density is zero. In principle then the altitude distribution of SO₂ is completely determined by specifying the ground-level SO₂ density and the mixing height altitude. As we will see later, the ratio is not sensitive to the SO₂ altitude profile so long as the bulk of the SO₂ is concentrated in the first few kilometers above the ground. Therefore the assumption above is not critical. Furthermore, we as-

sume the air, aerosol and ozone altitude profiles of Shettle and Green (1974); that the ground albedo is .05 and that the aerosol is characterized by the cumulative size distribution

$$N(r) = N_0 [1 + (r/a)^v] \quad (1)$$

with $v = 3$ and $a = .03 \mu\text{m}$ and has an index of refraction $m = 1.5 - .01i$. We will discuss later in this paper how deviations of the real atmosphere from our model atmosphere affect the determination of the SO_2 optical thickness from ratio measurements. We use the multiple-scattering technique as described in Shettle and Green (1974) to calculate the diffuse irradiance.

The dependence of the ratio on SO_2 at 315.1 nm for an overhead sun is shown in Fig. 1. The ratio is plotted versus the optical thickness of SO_2 for a mixing height of 1 km and for a number of solar zenith angles and for an aerosol optical thickness of 0.4. The ratios are monotonically decreasing functions of the SO_2 optical thickness, $\tau(\text{SO}_2)$, except for the 60° solar zenith angle curve. The dashed line in Fig. 1 corresponds to a solar zenith angle of 60° where the ratios have been divided by three. The ratio has a shallow minimum and then begins to rise with increasing SO_2 optical thickness. Consequently for SO_2 optical thicknesses in the 0 to 0.2 region, the ratio cannot be used to infer $\tau(\text{SO}_2)$ to an accuracy better than 0.2. However, for the smaller solar zenith angles, SO_2 optical thicknesses can be determined to ± 0.02 to 0.04 if we assume that ratio measurements at 315.1 nm are accurate to $\sim 1\%$; which is not unrealistic with a double monochromator.

An increase in the aerosol concentration leads to a corresponding increase in the diffuse to direct ratio. In Fig. 2 the ratio dependence on the SO_2 optical thickness is shown for aerosol optical thicknesses of 0.1, 0.4, 0.7, and 1.0. The major effect is a shift in the magnitude of the ratio; the monotonically decreasing nature of the curves is preserved throughout.

The altitude to which the SO_2 is mixed has little effect on the value of the diffuse to direct ratio. That the ratio depends mainly on the total SO_2 optical thickness and is practically independent of the mixing height is seen in Fig. 3. Deviations as the mixing height is increased above 1 km become greater than 1% as the mixing height becomes greater than 5 km for the larger values of the SO_2 optical thickness. It is very unlikely that SO_2 mixing heights of this magnitude will be encountered in the real atmosphere in view of the high water solubility of SO_2 . In fact, Stedman, Chameides and Cicerone (1975) have suggested that the SO_2 mixing ratio should have a steep negative gradient with altitude due to the moderately strong solubility of SO_2 in water. The observation that the ratio is insensitive to the SO_2 mixing height at altitudes below a few kilometers is significant in that we can infer the SO_2 mixing height if we know the ground-level SO_2 and the diffuse to direct ratio at 315.1 nm. If, indeed, the SO_2 mixing ratio decreases with altitude much like water vapor and say decreases as $\exp(-y/h)$ where y is the altitude, then the mixing scale height h can be inferred.

The relationship between the SO_2 density at the ground and the total optical thickness of SO_2 for well mixed conditions is shown in Fig. 4 for a number of mixing heights.

In order to use ratio measurements to infer the SO_2 optical thickness, other variable atmospheric constituents such as ozone and particulates that may significantly affect the value of the ratio must be determined by independent means. We will discuss aerosol effects in the next section. The stratospheric ozone has only a small effect on the ratio at 315.1 nm. Calculated ratios for stratospheric ozone thicknesses of 0.25 atm-cm and 0.35 atm-cm differ by less than a percent. To see what effect the tropospheric ozone will have, assume that the thickness of the tropospheric ozone is 0.032 atm-cm. The absorption coefficient for ozone at 315.1 nm is $\sim 1.3 \text{ cm}^{-1}$. This leads to an optical depth

of .042. Thus if we make the unrealistic assumption of zero troposphere ozone in our model, the experimental ratio measurements when compared with calculated ratios will infer an SO₂ optical thickness which is at most only .04 too large. More realistically, the error due to tropospheric ozone assuming some average value would be considerably smaller.

3. AEROSOL EFFECTS

As we have mentioned previously, an increase in the aerosol concentration leads to an increase in the ratio of diffuse to direct irradiances. Therefore, it is important to know how to model the atmospheric aerosol component. Of primary importance is the aerosol optical thickness. The optical thickness is related to the total extinction cross section as calculated using Mie theory and the number of particles of the aerosol in a vertical column. It is also important to know the relative frequency of scattering and absorption, that is to say the albedo for single scattering. The single scatter albedo is the ratio of the scattering cross section to the total extinction cross section and depends on the imaginary part of the index of refraction and the size distribution of the aerosol particles. In Table 1 we list for 315 nm the single scatter albedos for our model aerosol and some other aerosols which differ from the model in either the imaginary refractive index or the parameters of the size distribution of Eq. (1). The range of single-scatter albedos is 0.889 to 1.0.

Determination of the aerosol optical thickness at 315.1 nm can be done using photometric techniques or by the following extrapolation method. In the extrapolation method aerosol optical thicknesses at selected wavelengths greater than 320 nm (i.e. in a region where SO₂ and ozone absorption may be neglected) are inferred from diffuse to direct ratios measurements. Extrapolation to smaller wavelengths (in the present case to 315.1 nm) is done assuming a wavelength power law dependence of the form

$$\frac{\tau}{\tau_0} = \left(\frac{\lambda}{\lambda_0} \right)^{\mu} \quad (2)$$

Here μ is determined to be the best power law fit to the Mie extinction cross sections in a small wavelength range, e.g. 300 to 340 nm and τ_0 is the aerosol optical thickness at a reference wavelength. For our model aerosol, $\mu = 0.87$.

In order to improve our modeling of the aerosol when analyzing experimental ratio measurements, aureole photographs (Green, Deepak and Lipofsky (1971)) can be taken to complement the ratio measurements. McPeters and Green (1976) have shown that the parameters a and v of the aerosol size distribution of Eq. (1) can be determined from the photographic aureole data. Furthermore, knowing a and v will lead to a realistic single scatter albedo to be used in calculating ratios and also will improve extrapolation of aerosol optical depths since the effective power in Eq. (2) can be determined for a particular set of a and v values.

The aerosol altitude distribution used in our model is shown as the solid line in Fig. 5. The scale height for this aerosol is 1 km. Increasing the scale height to 2 and 3 km, give rise to the profiles shown by the dashed and dotted lines respectively. The maximum change in the ratio as the scale height is increased from 1 km to 2 km is on the order of 1% and from 1 to 3 km is on the order of 2%. Thus we see that the aerosol altitude distribution has a small effect on the ratio.

Our investigations have also shown that the ratio is insensitive to detailed structure of the aerosol scattering phase function. This result is not surprising since the diffuse irradiance is the sum over all downward directions.

4. ANALYTIC REPRESENTATION OF THE RATIO

Assuming we have modeled the atmosphere in a realistic manner, the diffuse to direct ratio at 315.1 nm will depend on three variables: the solar zenith angle θ_s , the aerosol optical thickness τ_{aer} , and the SO₂ optical thickness $\tau(SO_2)$.

We have found that the ratio dependence on the SO₂ optical thickness can be represented by a three parameter quadratic function of the form

$$\ln R = A + B \tau(SO_2) + C \tau(SO_2)^2 \quad (3)$$

where R is the ratio, and A , B and C are adjustable parameters. This function can represent the calculated ratios to within 1% over the complete range of SO₂ optical thicknesses from 0 to 0.5 which we have considered. The parameters A , B and C will depend on the aerosol optical thickness and solar zenith angle. In order to simplify the dependence of the parameters on τ_{aer} and θ_s we have replaced A and B with two new parameters R_0 and θ_1 defined by the following equations:

$$B = \sec \theta_s - \sec \theta_1 \quad (4)$$

$$A = \ln R_0 + \tau_0 B \quad (5)$$

and Eq. (3) becomes

$$\ln R = \ln R_0 + (\tau_0 + \tau(SO_2)) (\sec \theta_s - \sec \theta_1) + C \tau(SO_2)^2 \quad (6)$$

Here τ_0 is the total optical thickness of the atmosphere excluding the SO₂ contribution. Imposing the constraint that C and R_0 be independent of $\tau(SO_2)$ we arrive at the following representation:

$$R_0 = 3.58 \exp(1.41 \tau_{aer}) \quad (7)$$

$$C = .704 \exp(-.841 \tau_{aer}) \quad (8)$$

$$\theta_1 = t_1 + \left(\frac{\theta_s}{t_2} \right) t_3 \quad (9)$$

where θ_1 and θ_s are in degrees and t_1 , t_2 and t_3 are the following functions of τ_{aer} :

$$t_1 = 62.13 - 12.61 \tau_{aer} + 5.18 \tau_{aer}^2 \quad (10)$$

$$t_2 = 56.76 - 50.09 \tau_{aer} + 26.49 \tau_{aer}^2 \quad (11)$$

$$t_3 = 3.66 - 2.89 \tau_{aer} + 1.74 \tau_{aer}^2 \quad (12)$$

In all, this is a 13 parameter representation which agrees with the theoretical ratios to about 1% for the range of aerosol optical thicknesses from 0 to 1.0 and solar zenith angles from 0° to 60°.

This analytic representation of the ratio facilitates the determination of the SO₂ optical thickness when θ_s , τ_{aer} and the ratio are specified. Eq. (3) is a quadratic algebraic expression for $\tau(SO_2)$ and will yield two roots.

$$\tau(SO_2) = \frac{-B \pm \sqrt{B^2 - 4C(A - \ln R)}}{2C} \quad (13)$$

where B and A are defined by Eqs. (4) and (5) in terms of θ_1 and R_0 . In the region, $0 < \theta_s < 60^\circ$, B is negative and the appropriate SO_2 optical thickness is given by the above equation choosing the negative sign. Choosing the positive sign gives optical thicknesses which are unrealistically large.

5. DISCUSSION

We have demonstrated that at a wavelength of 315.1 nm the ratio of the diffuse to direct irradiances at the ground is sensitive to the optical thickness of SO_2 in the vertical column. Inference of the SO_2 optical depth from ratio measurements is practical in view of the facts that the ratio is insensitive to the details of the SO_2 and aerosol altitude profiles, the stratospheric ozone and the aerosol scattering phase function. The two most important aerosol properties that need to be determined when using the 315.1 nm ratio to infer the SO_2 thickness are the aerosol single scatter albedo and the aerosol optical depth. Of these the aerosol optical depth is the most variable and most critical. Ratio measurements at selected wavelengths greater than 320 nm where ozone and SO_2 absorption are negligible can be used to infer aerosol optical thicknesses there and by careful extrapolation the aerosol optical thickness at 315.1 nm can be inferred. Then knowing the aerosol optical thickness at 315.1, the SO_2 optical thickness can be obtained by algebraic inversion of Eq. (3). If photographic aureole methods are employed simultaneously with the diffuse to direct ratio measurements then the parameters a and v of the aerosol size distribution of Eq. (1) can be determined. This would have a two-fold benefit. Firstly, knowledge of the size distribution would enable us to calculate a more reliable value for the single scatter albedo and this in turn would increase the accuracy of our ratio calculations. Secondly, the effective power law dependence of the aerosol optical depth on wavelength could be calculated for the measured size distribution.

A more difficult variable to determine is the ground albedo. Furukawa and Heath (1973) have made measurements of the ground albedo for various natural surfaces in the wavelength region 310-380 nm. They found that for scrub desert the ground albedo was .04 over the 310 to 380 nm range and for farmland 70% tilled and 30% covered with vegetation the ground albedo was between 0.07 to 0.08 for the 310 to 340 nm region. We have assumed a ground albedo of 0.05 in our calculations. Varying the true ground albedo by ± 0.05 from our assumed ground albedo leads to a variation in the inferred SO_2 optical thickness of approximately ± 0.03 .

If point-sampling of the ground-level SO_2 density is made simultaneously with the ratio measurements (e.g. flame photometry), then some inference on the vertical extent of SO_2 can be drawn. This inference will depend on how the SO_2 mixing ratio behaves as a function of altitude - a question which has not been answered by experimental measurements.

The combination of ratio measurements in the middle ultraviolet, photographic aureole measurements and point-sampling of ground-level SO_2 forms a promising battery of experimental methods from which information on the state of the lower troposphere can be obtained.

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TABLE I. THE AEROSOL SINGLE SCATTER ALBEDO a_{ss} FOR A NUMBER OF SIZE PARAMETERS a AND v OF EQ. (1) AND INDICES OF REFRACTION m .

a	v	m	a_{ss}
.03	3.0	1.5 - .01i	.906 (Model)
.03	2.8	1.5 - .01i	.893
.03	3.0	1.5 - .01i	1.0
.1	3.0	1.5 - 0i	.889
.1	4.0	1.5 - .01i	.935
		1.5 - .01i	

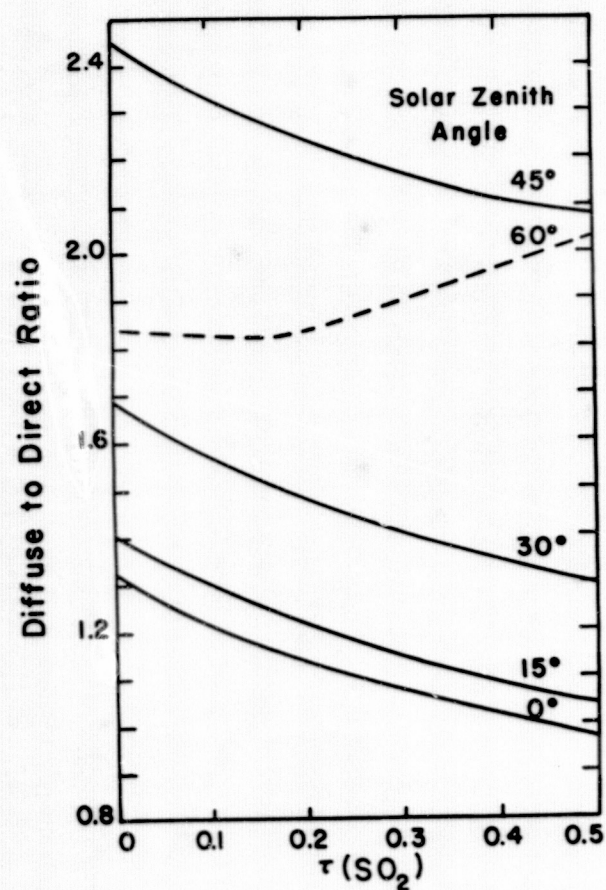


Fig. 1. Diffuse to direct ratio versus the total SO_2 optical thickness for the solar zenith angles 0° , 15° , 30° , 45° and 60° ; $\tau_{\text{aer}} = .4$.

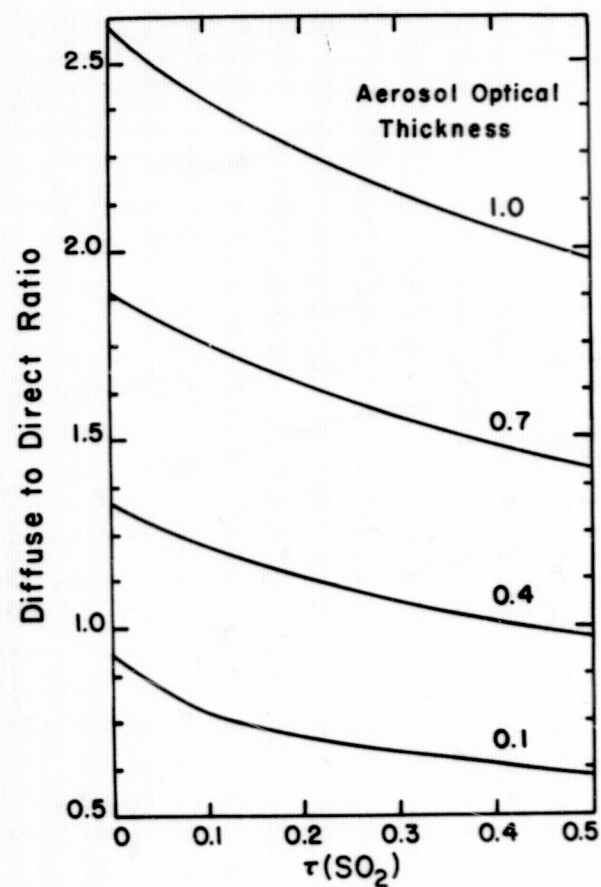


Fig. 2. Diffuse to direct ratio versus the total SO_2 optical thickness for the aerosol optical thicknesses - 0.1, 0.4, 0.7 and 1.0; solar zenith angle is 0° .

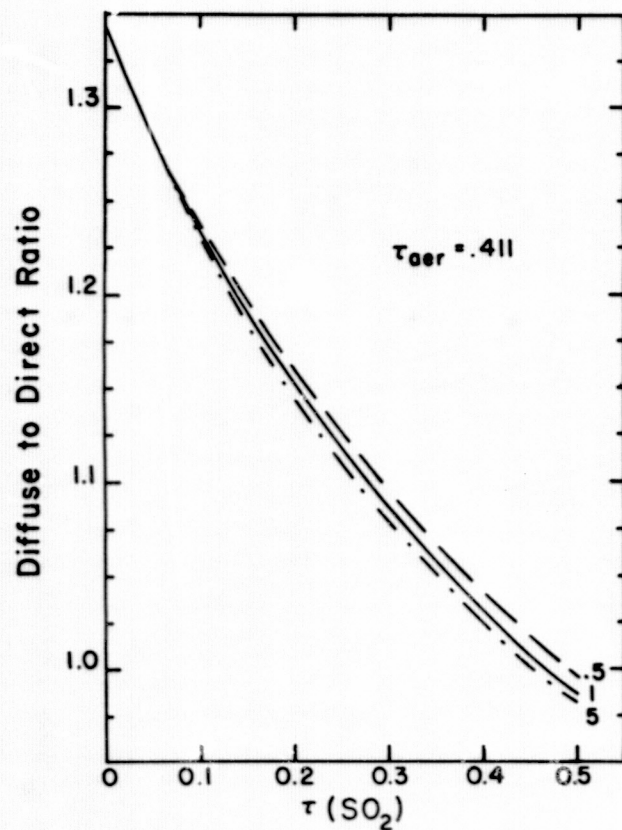


Fig. 3. Diffuse to direct ratio versus the total SO_2 optical thickness for three mixing heights - .5 km (---), 1.0 km (—) and 5 km (-.-.); $\tau_{\text{aer}} = .411$, $\theta_s = 0^\circ$.

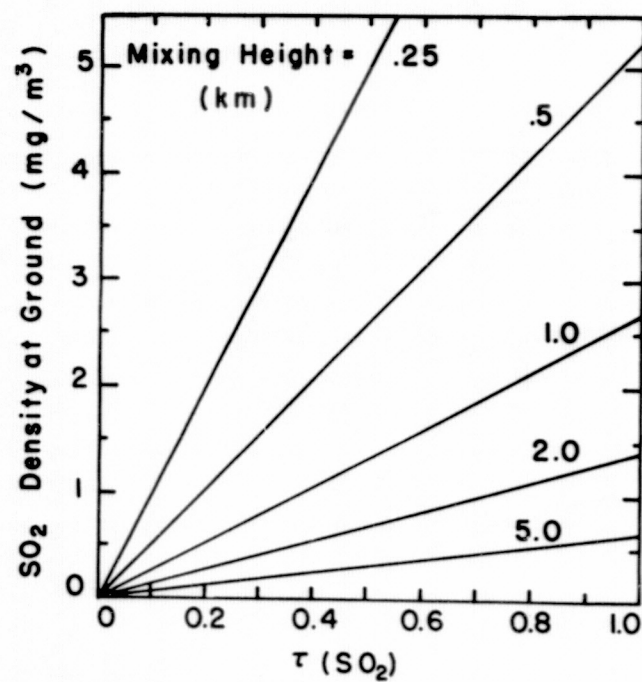


Fig. 4. The relationship between the SO_2 optical thickness in a vertical column and the SO_2 density at the ground assuming the SO_2 is well mixed to a mixing height of 0.25, 0.5, 1.0, 2.0 and 5.0 km, and above the mixing height the SO_2 density is zero.

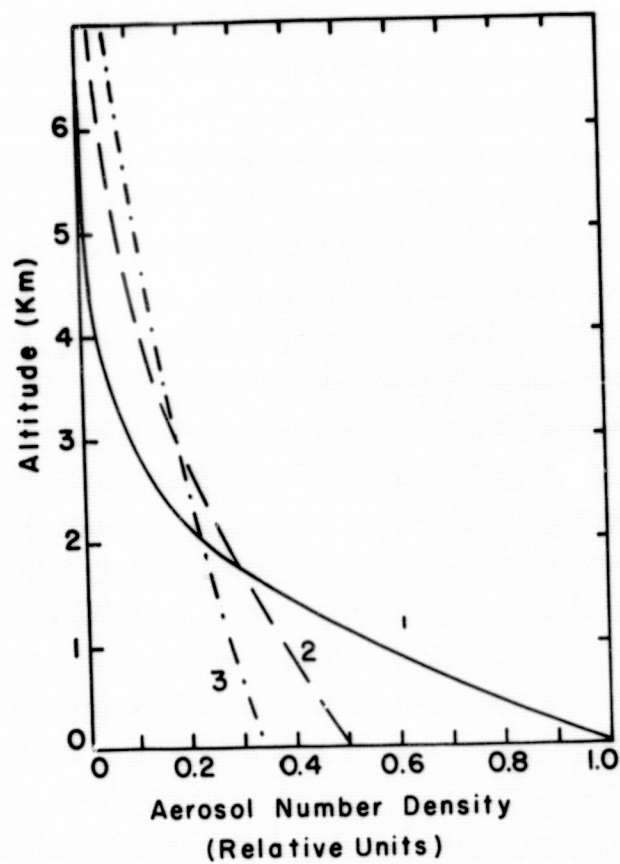


Fig. 5. The aerosol number density in relative units as a function of altitude for scale heights of 1.0 km (—), 2.0 km(---) and 3.0 km (···).

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N78-14503

THE VECTOR CLASSIFIER

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ABSTRACT

A linear classifier is developed. The classifier algorithm derives, from the picture element (pixel) response values, the response values for a point (called footpoint) consisting of determined proportions of distinct and operator defined land surfaces. The algorithm decides whether the pixel contains the content of the defined surfaces by testing the footpoint to pixelpoint distance against an operator specified threshold value. The test can be either of statistical or geometric form. Those pixels which give a positive result to the test are sub-classified according to the proportions of the distinct land surfaces.

The practical characteristics of the classifier are discussed and the classification results achieved, in a number of test areas, are described.

The artificial nature of the classifier assumptions relate to certain land surface conditions. Testing the suitability of the classifier for other conditions is discussed.

1. INTRODUCTION

Landcover is defined as the terrain surface and everything supported thereon that will influence the solar spectral reflectance from that point or area. Most landcovers exhibit a gradual change in both vegetative cover and soil type, and not well defined boundaries. The sampling characteristics of LANDSAT MSS imagery reinforces this pattern so that the pixel response values do not form discrete clusters, but exhibit a more homogenous distribution.

This is illustrated in Figure 1, a two dimensional histogram of band 5 against band 7 for all the data in strip 1 of 4 of Frame 1129-23494 (Nov. 1972). The author has modified the digital data described in Figure 1 so that the values in all bands cover the range 1-64, but maintained the linearity of the data within each band.

The author will show that a pixel containing proportions of different types of landcover will have a response value that is related linearly to the proportions of the component landcovers. To assist, a hypothetical "uniform surface" is defined as a surface over which those factors influencing spectral reflectance in the nominated waveband, are constant. The response values for a "uniform surface" are assumed to be normally distributed, being adequately described by a mean and covariance array.

Geometrically, LANDSAT MSS imagery can be conceived as defining a four dimensional image space, with each dimension representing a waveband. A "uniform surface" will form an ellipsoidal cluster in this four dimensional space, with the ellipsoid centre specified by the mean array for the "uniform surface".

It will be seen that the derivation produces the same response relationship for a pixel containing proportions of different types of landcover as that found statistically by HORWITZ et al (3-4). The author has developed the application of this relationship in a general classifier algorithm, not restricted to proportion estimation.

2. THEORETICAL DERIVATION

The power received by a scanner from an instantaneous field of view (IFOV) covered by a "uniform surface" of apparent radiance, N_λ at height h is given by:-

$$P_\lambda = \int_0^\Omega \int_0^{AC} N_\lambda \eta_o d\theta^2 \quad \dots 1$$

where: $N_\lambda = N_\lambda(o) t_\alpha + N_\lambda^a(h)$

$N_\lambda(o)$ = radiance of "uniform surface" at zero altitude.

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- t_{α} = atmospheric transmission coefficient at height, h
 $N_{\lambda}(h)$ = radiation scattered into IFOV and emitted by the intervening atmosphere.
 η_o = optical efficiency of scanner.
 A_c = area of collecting optics of scanner.
 Ω = solid angle field of view scanner.

If the IFOV contains two or more "uniform surfaces" of surface radiances $N_{1\lambda}$, $N_{2\lambda}$, etc. then the power received is given by:-

$$P_{\lambda} = \int_0^{\Omega_1} \int_0^{A_c} N_{1\lambda} \eta_o \phi_a d\theta^2 + \int_0^{\Omega_2} \int_0^{A_c} N_{2\lambda} \eta_o \phi_a d\theta^2 + \dots$$

Integrating for n "uniform surfaces":-

$$P_{\lambda} = (N_{1\lambda} \Omega_1 + N_{2\lambda} \Omega_2 + \dots + N_{n\lambda} \Omega_n) \eta_o A_c \quad \dots 2$$

If the surface area of the IFOV is A, and the sub-IFOV areas covered by "uniform surfaces" 1, 2, ..., n are $A_1, A_2, \dots, A_n$, then:-

$$\frac{\Omega_i}{\Omega} = \frac{A_i}{A}, \quad i = 1, 2, \dots, n$$

Substitute into 2 to give:-

$$P_{\lambda} = \left(\frac{A_1}{A} * N_{1\lambda} + \frac{A_2}{A} * N_{2\lambda} + \dots + \frac{A_n}{A} * N_{n\lambda} \right) \Omega \eta_o A_c \quad \dots 3$$

so that the power received by the IFOV is linearly proportional to the ratios of the sub-IFOV areas of the different "uniform surfaces". The LANDSAT MSS digital data has been calibrated so that the pixel response values, R, are linearly related to radiance and hence power received. Therefore:-

$$R_{\lambda} = \frac{A_1}{A} * R_{1\lambda} + \frac{A_2}{A} * R_{2\lambda} + \dots + \frac{A_n}{A} * R_{n\lambda}$$

and

$$\frac{A_i}{A} = a_i, \quad i = 1, 2, \dots, n \text{ so that:-}$$

$$R_{\lambda} = a_1 R_{1\lambda} + a_2 R_{2\lambda} + \dots + a_n R_{n\lambda} \quad \dots 5$$

and the proportions must sum to unity so that:-

$$\sum_{i=1}^n a_i = 1 \quad \dots 6$$

$$\therefore R_{\lambda} = a_1 (R_{1\lambda} - R_{n\lambda}) + a_2 (R_{2\lambda} - R_{n\lambda}) + \dots + a_{n-1} (R_{n-1,\lambda} - R_{n\lambda}) + R_{n\lambda} \quad \dots 7$$

If we consider m discrete wavebands then:-

$$\begin{aligned}
 R_1 &= a_1 (R_{1,1} - R_{n,1}) + a_2 (R_{2,1} - R_{n,1}) + \dots + a_{n-1} (R_{n-1,1} - R_{n,1}) + R_{n,1} \\
 R_2 &= a_1 (R_{1,2} - R_{n,2}) + a_2 (R_{2,2} - R_{n,2}) + \dots + a_{n-1} (R_{n-1,2} - R_{n,2}) + R_{n,2} \\
 &\vdots \\
 R_m &= a_1 (R_{1,m} - R_{n,m}) + a_2 (R_{2,m} - R_{n,m}) + \dots + a_{n-1} (R_{n-1,m} - R_{n,m}) + R_{n,m}
 \end{aligned} \quad \dots 8$$

A pixel with response values $(R_1, R_2, \dots, R_m)$ contains proportions $a_i, i=1, n$ different surfaces with response values $(R_{i,1}, R_{i,2}, \dots, R_{i,m}), i=1, n$. Each of the n "uniform surfaces" is defined as a node. The response values for the nodes must be specified prior to classification.

In equation 8, n must satisfy:-

$$n \leq m + 1 \quad \dots 9$$

The nodes define a geometric figure in m-dimensional space, which extends beyond the subset of the figure contained within the nodes. This subset is called domain of the nodes.

If each node is considered to be a vector, $N_1, N_2, \dots, N_n$, then the vector $P = a_1 N_1 + a_2 N_2 + \dots + a_n N_n$ will be on the surface of the geometric figure defined by the nodes only when:-

$$a_1 + a_2 + \dots + a_n = 1$$

Therefore solution of equation 8 will yield a point or points that lie on the geometric figure defined by the nodes. The optimum point will be that for which the euclidean distance to the pixel point is a minimum, and is known as the footpoint. The footpoint will be found by a least squares solution of equation 8. The principle of least squares² is that the most probable values of the unknowns are those for which the sum of the weighted squares of the residuals is a minimum. If values $(R_1, R_2, \dots, R_m)$ are the most probable values as found by

a least squares solution of equation 8, then that solution minimises:-

$$\{(R_1 - R'_1)^2 + (R_2 - R'_2)^2 + \dots + (R_m - R'_m)^2\}$$

Assuming unit weights or that the covariance arrays for all nodes are equal. The footpoint may however, be beyond the domain of the nodes. In this case one or more of the proportions will be negative, and one or more may be greater than 1.0.

It is necessary to find a domain footpoint $(r_1, r_2, \dots, r_m)$ that lies on the geometric figure, and within the domain of the nodes. The domain footpoint proportions should have the characteristics:-

- (1) $0 < a_i \leq 1.0$ for $i = 1$ to n
- (2) $\sum_{i=1}^n a_i = 1.0$

The optimum domain footpoint will be that point for which:-

$$\{(R_1 - r_1)^2 + (R_2 - r_2)^2 + \dots + (R_m - r_m)^2\} \text{ is a minimum.}$$

2.1 Relationship between Node Surface and Proportion

As the number of nodes increases from $n=2$ to $n=m$ so the node defined geometric figure changes from a directed line, to a plane, to a three dimensional volume, etc. The domain of this surface will be a line segment, a plane triangle, a tetrahedron, etc.

The footpoint will coincide with the pixelpoint when the pixelpoint lies on the geometric figure. When the pixelpoint does not lie on the geometric figure the sign of the proportions will depend upon the position of the footpoint relative to the domain nodes. If the footpoint is within the domain, then all will be positive, and if without then some will be negative. Negative proportions indicate that the footpoint lies across, and beyond, the domain from the corresponding node.

As n increases, the subset of values contained within the nodes geometric figure will increase relative to the total set of values in m dimensional space. Therefore, in general, as n increases, so the footpoint - pixelpoint distance will decrease.

When $n=m+1$ then every pixelpoint lies on the nodes geometric figure and the footpoint - pixelpoint separation will be zero. If the pixelpoint lies outside the domain of the nodes, some of the proportions will be negative, and determination of the domain footpoint is essential for meaningful classification.

3. CLASSIFIER DEVELOPMENT

Equation 8 can be stated in matrix notation as:-

$$A * U = R \quad \dots 10$$

where U is the column matrix of unknown proportions.

If:-

$$B = A^T * A$$

then to achieve a least squares solution:-

$$U = B^{-1} * A^T * R \quad \dots 11$$

Let:-

$$C = B^{-1} * A^T$$

$$\therefore U = C * R \quad \dots 12$$

Array C is constant for any vector and can be determined prior to classification. Solution of equation 12 for each pixel will give the footpoint proportions $a_1, a_2, \dots, a_{n-1}$, from which a_n can be found using equation 6.

If one or more of the proportions are negative then the proportions of the domain footpoint have to be found. Currently this is done by:-

- (1) Assigning zero to all negative proportions.
- (2) Make the proportions sum to unity by dividing each proportion by the sum of the non-negative proportions.

However this procedure does not yield the optimum domain footpoint, and at the extremities of the domain can give significantly greater domain footpoint - pixelpoint distances than the

optimum. It is therefore, a less than satisfactory procedure. The domain footpoint - pixelpoint distance is tested either statistically or geometrically against a threshold value to determine whether the pixel belongs to that class or not.

Practical difficulties will frequently occur in defining node covariance arrays. The assumptions on which the derivation of the algorithm are based, implies that these covariance arrays would be approximately equal. The Law of Propagation of Error² allows determination of the domain footpoint covariance array for independent node surfaces. This covariance array would be smaller in magnitude than that of the nodes. As the author discusses in section 4, however, when the nodes are not independent the covariance array can be expected to be of the same or larger magnitude than the node covariance arrays. Utilizing the covariance arrays would significantly increase computer time, both in deriving the proportions and in testing the domain footpoint - pixelpoint distance. The author believes that the increase in precision that would be achieved would not justify this cost and has accordingly adopted geometric thresholds.

Those pixels that are classified as belonging to a particular vector class can be sub-classified using the derived proportions of the domain footpoint for the pixel. The sub-classification could simply be in terms of these proportions, or it could be a functional relationship between the proportions and some environmentally oriented parameter, giving a final sub-classification defined in terms of this parameter. The present program sub-classifies in terms of the proportions of the node surface but the difficulty is in distinctly presenting each sub-class when the number of nodes become large. If the proportions are grouped into ρ intervals within the range of 0.0 to 1.0, and there are n nodes then there are $\{\rho (n-1) + 1\}$ distinct sub-classes to be portrayed. The one additional subclass above $\{\rho (n-1)\}$ is for the case where $a_n = 1.0$.

The author's approach is to form separate classification images for each node, on which the different proportion intervals are represented by a different symbol or change in tone.

The images are combined by printing in colour, and the discriminability of the sub-classes can be maintained by careful selection of the hues if it is remembered that the proportions are restricted by the necessity for them to sum to 1.0.

4. ENVIRONMENTAL SUPPORT FOR CLASSIFIER

The classifier algorithm is based on the assumption that the nodes are discrete and radiometrically independent surface types, such as sand and scrub.

For maximum benefit the classifier should be capable of reliably distinguishing between the limits of a natural or artificial change in the landcover. For example, between healthy vigorous pasture and dry, dead pasture, or between bare soil and pasture of high biomass. The many factors influencing LANDSAT response from pastures makes analysis for linearity conditions difficult, but essential, prior to reliable classification. Two cases in which response changes in an approximately linear manner with change in environmental conditions have been investigated.

- (1) Sample areas have been selected for nine turbid lakes in Western Victoria on frame 1129-23494 and the sample mean response values for the lakes have been plotted in Figure 2, band 5 against the response values for the other bands.
- (2) Bool Lagoon, in the south east of South Australia is a large lagoon which is covered with varying densities of bull rushes and sedges for most of its area. The remainder is clear water with a dark floor. Profiles taken across Bool Lagoon on frame 1129-23494 have exhibited linearity between the response values as shown in Figure 3, plotting band 7 against the other bands. This data suggests that two linearities were occurring in the lagoon, however subsequent classification patterns indicate that it is more likely that only one approximate linearity exists.

When classifying between the limits of a natural or artificial change in landcover then the nodes cannot be assumed independent. If the linearity is a function of the changing landcover then each intermediate landcover type can be considered as a "uniform surface" and its covariance array could be expected to be of the same magnitude as the covariance arrays for the nodes.

The author believes that in practice the reason for the linearity in response changes with changes in the natural or artificial landcover will lie between these limits and that the use of a constant geometric threshold will introduce insignificant errors in classification.

5. RESULTS ACHIEVED

The classifier has been used to test its reliability in two types of situations namely that of discrete and independent surfaces, and where a natural or artificial surface has an observed linearity between response values on LANDSAT.

5.1 Classification of Coastal Sand and Scrub

An area of coastal sand dune bounded on the south by the Southern Ocean, and on the north by Lake Bonney, was selected because it is covered in part by scrub of predominantly the paperbark type. The area was covered by 1:10 200 colour aerial photography. The two nodes were selected from training sets of the data and the classification done using the parameters given in table 1.

The subclass boundaries on the resultant lineprinter image were digitised, transformed and plotted at photoscale onto clear film. This boundary map was overlaid on the airphotos and from the airphotos estimates were made of the percentage sand area (to the nearest ten percent) within each pixel.

The technique suffers a number of sources of error namely:-

- (1) The simple transformation was designed to correct for the shift every sixth scanline due to earth rotation, and the differential scales along and across axis in the lineprinter image.
- (2) Matching of the boundary overlay to the aerial photography therefore contained errors and displacements due to the nature of the LANDSAT imagery, the aerial photography and the positioning judgements made by the author.
- (3) The subjective nature of judging the percentage sandcover meant that a greater dispersion was found in the centre of the domain than at either end.

However, the results, given in Table 2, show a correlation between the LANDSAT classification and the aerial photographic assessment. The line of best fit between the two would not be 1:1, because the sand in the area of study exhibited changes in radiance with changes in texture. The sand exhibiting higher response values on LANDSAT, were selected as the node. Consequently other areas of sand which had a lower response values fell adjacent to points further down the vector and thus were often classified as containing ten or twenty percent scrub.

5.2 Classification of Bool Lagoon

Using the linearity between band response values as found across Bool Lagoon in frame 1129-23494, nodes were selected and the lagoon classified, the eastern half being shown in Figure 4. Maintenance of the linearity was assumed for two subsequent LANDSAT 2 frames, 2342-23411 and 2359-23351.

Node response values were selected from the LANDSAT data within the lagoon. Using these parameters, incorporated into Table 3, the classification of both frame segments was undertaken and the results for the eastern half of the lagoon are shown in Figures 5 and 6.

The three classifications contain expected variations from one date to another within the lagoon and the surrounding swamp areas. However the results are very consistent with the patterns of water surface and varying densities of bullrushes that have been observed on colour and colour IR aerial photography of the lagoon. The area around the lagoon that is not classified are grazing paddocks.

Detailed field evaluation of the significance of the classification has not yet been done. The author has observed, however, that, given the limits of spatial resolution of the LANDSAT imagery, very subtle variations in radiance, recorded as small changes in hue, brightness and saturation on the 1:40 000 colour aerial photography of the lagoon, are also seen as changes in classification. Particularly if the classification resolution is increased to 20 classes within the same vector distance, as has been done on frame 1129-23494.

6. CONCLUSIONS

The classifier has been shown to work for both dissimilar surface and naturally or artificially changing surface conditions. However, a prerequisite for reliable classification of the second type of surface would be to establish that an approximate linearity existed between the response values for the different node conditions. This understanding of the relationship between the node surfaces should, with the subsequent classification and associated fieldwork

result in a better appreciation of the existing environmental conditions.

Each vector surface, representing a whole range of different landcover conditions is contained in a simple array statement in the program. Sub-classes can be readily defined in terms of the proportions, and very fine classification resolution can be achieved without a significant increase in required computer store. The classification is in terms of response of the node surfaces, so that a further step may be required to relate this to quantitative physical parameters. This transformation may well be non-linear, and can be done either as part of, or subsequently to, the classification, which is an advantage because it would normally require field data to establish the transformation parameters.

The current classifier program is rather slow and crude, taking 25 sec of central processor time to classify and display an area of 7,200 pixels. The author believes that the time used for classification can be significantly reduced, but it is unlikely to be as fast as some of the simpler parallelopiped type classifiers. The vector classifier is therefore unlikely to be cost-effective for generalised classification work involving about 20 different landcover classes. Its strength is in much higher resolution classification.

7. ACKNOWLEDGEMENTS

The current work has been done as part of LANDSAT follow on project 2896-D. The author would like to acknowledge the assistance of the National Aeronautics and Space Administration and the Principal Investigations, the Engineering and Water Supply Department and Department of Agriculture and Fisheries. Mr. B. Benjamin assisted by providing helpful comments on the mathematical procedures employed.

8. REFERENCES

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BAND	RESPONSE SCRUB NODE	VALUES SAND NODE	VECTOR LENGTH	THRESHOLD DISTANCE	NUMBER OF SUBCLASSES	SUBCLASS INTERVAL
4	13.7	44.1	69.2	3.0	11	6.3
5	10.1	54.6				
6	18.3	52.6				
7	21.0	47.6				

TABLE 1. PARAMETERS FOR VECTOR CLASSIFICATION
OF SAND-SCRUB TEST AREA

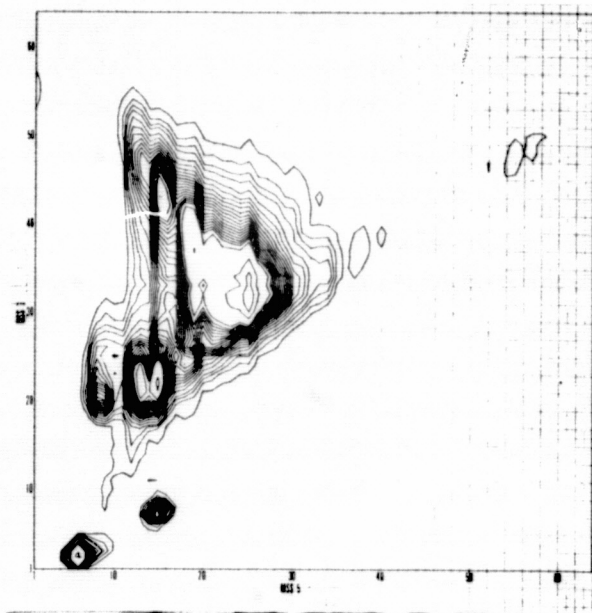
Class	0-5	6-15	16-25	26-35	36-45	46-55	56-65	66-75	76-85	86-95	96-100
0	24	7	0	0	0	0	0	0	0	0	0
1	7	49	1	-	-	-	-	-	-	-	-
2	1	2	7	7	7	1	1	0	-	-	-
3	-	2	7	9	4	3	1	2	1	-	-
4	-	-	1	9	8	7	13	6	5	2	-
5	-	-	-	3	6	3	8	20	2	-	-
6	-	-	-	-	1	6	11	18	2	1	-
7	-	-	-	-	3	2	7	8	11	4	-
8	-	-	-	-	-	2	1	4	2	16	6
9	-	-	-	-	-	-	-	-	-	13	52
\$	-	-	-	-	-	-	-	-	-	1	6

Percentage Assessed Cover

TABLE 2. CORRELATION OF SAND-SCRUB CLASSIFICATION
WITH AIR PHOTO ASSESSMENT

FRAME	BAND	RESPONSE	VALUES	VECTOR LENGTH	THRESHOLD DISTANCE	NUMBER OF SUBCLASSES	SUBCLASS INTERVAL
		WATER	RUSHPS				
1129-23494 (29 Nov. 1972)	4	9.5	18.2	53.59	4.5	10	5.4
	5	4.5	19.3				
	6	3.5	41.2				
	7	2.0	36.0				
2342-23411 (30 Dec. 1975)	4	5.0	9.0	49.37	4.5	10	4.9
	5	4.0	10.0				
	6	2.0	35.0				
	7	0.0	36.0				
2359-23351 (16 Jan. 1976)	4	5.0	9.0	49.37	4.5	10	4.9
	5	4.0	10.0				
	6	2.0	35.0				
	7	0.0	36.0				

TABLE 3. PARAMETERS FOR VECTOR CLASSIFICATION
OF BOOL LAGOON TEST AREA



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FIGURE 1.

DISTRIBUTION OF LANDSAT IMAGE DATA. The distribution of data in band 5 against band 7 is depicted as a contoured two dimensional histogram. The isolated clusters are the ocean and Lake Bonney.

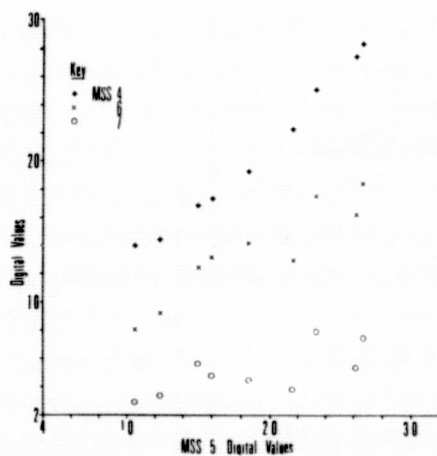


FIGURE 2.

MEAN RESPONSE VALUES FOR NINE TURBID LAKES IN WESTERN VICTORIA. On each lake sample areas were used to derive mean response values in all bands. The mean values in bands 4, 6 and 7 are plotted against band 5.

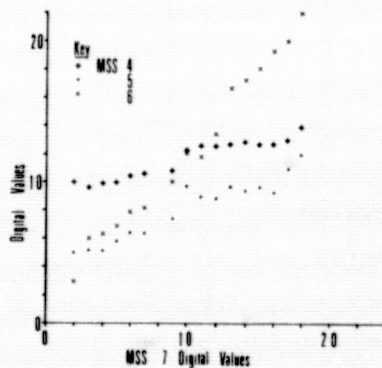


FIGURE 3.

PLOT OF RESPONSE VALUES ACROSS BOOL LAGOON. The response values for bands 4, 5 and 6 are plotted against band 7.

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FIGURE 4.
CLASSIFICATION OF BOOL LAGOON ON 29 NOV.
1972 (FRAME 1129-23494).



FIGURE 5.
CLASSIFICATION OF BOOL LAGOON ON 30 DEC. 1975
(FRAME 2342-23411).

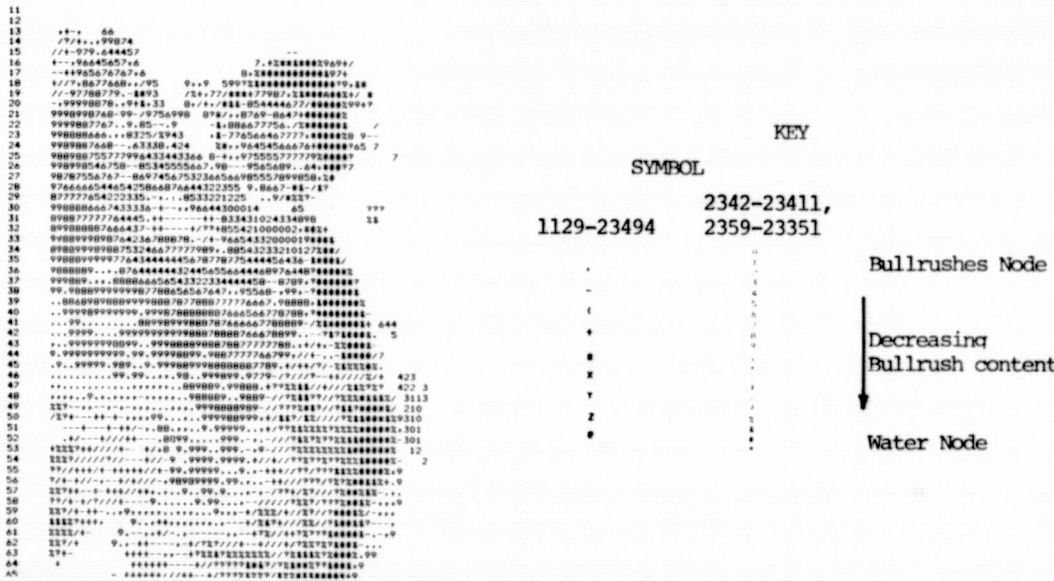


FIGURE 6.
CLASSIFICATION OF BOOL LAGOON ON 16 JAN.
1976 (FRAME 2359-23351).

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MULTI-SEASONAL DATA ANALYSIS AND SOME EXTENSIONS
FOR ENVIRONMENTAL MONITORING

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ABSTRACT

Time is always a parameter of the spectral reflectance of ground materials. So far, multi-spectral data have been used in various fields. On the other hand, combination data which consists of deferent temporal ones have been done in few cases. In several cases, however, time serial data is very useful for invesigation of the ground materials or knowing the surface phenomena.

Nowadays, multi-spectral data analysis has been well known technique of remote sensing data analysis. Multi-seasonal data analysis has been considered against it here. That is, the analysis is not based on the multi-spectral radiance data-set which parameter is wavelength, but on the spectral radiance data-set which parameter is season.

As basic concepts of the multi-seasonal data analysis:

1. Comparing multi-spectral data with multi-seasonal data.
2. Relationship between the periodisity of LANDSAT and the seasonal sense of the Orientals.
3. Method to register the data which have been acquired in different time.

and as the applications, following four examples are shown:

1. Quality investigation of paddy field by 3 seasonal LANDSAT data.
2. Progress check of paddy field by 3 LANDSAT data in harvest season.
3. Detailed survey of vegetational environment by summer and winter LANDSAT data.
4. Calculation of reclamation area 1972 to 1976 by LANDSAT 1 and 2 data.

1. INTRODUCTION

In case of surveying the phenomena on earth surface by using the data of spectral radiance which change according to time, the things about vegetation are the most interesting. The difference between deciduous trees and evergreen trees is evident in the existence of the leaf in winter season. Also, some differences by time are considerable among different evergreen trees or grasses. In addition to vegetation survey, geological features or characteristics of soil may be estimated in more detail, because such features or characteristics appear on the vegetation covering them.

In general, the phenomena occuring on the ground repeats themselves in the period of a year. Then, in order to monitor our regional environment in which we live, it is expected that more

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informations will be obtained in the case of analyzing the remote sensing data corresponding to four seasons rather in the case of analyzing the simple multi-spectral data. Furthermore, expanding the concept of seasonal sequentially arranged data and analyzing them, some valuable informations for each purpose will be obtained.

The reason why multi-seasonal data analysis is more difficult than usual multi-spectral data analysis exists in two points. One is the difficulty of acquiring timely remote sensing data. Another is the difficulty of accurate registration of two LANDSAT scenes.

After general overviews about the concept of multi-seasonal data, the relationship to multi-spectral data and techniques for registration etc., four examples are following in order.

2. PERIODICITY OF THE REFLECTIVE PROPERTIES OF VEGETATION

Spectral reflection properties of vegetation changes according to season. The period is one year and about same pattern repeats itself. This pattern depends on the kind of vegetation, climate characteristics of the region or the features of soil.

When supposing a typical pattern for vegetation, a model were considered as Figure 2. Spectral reflectance is a function of season. In spring, the value of infrared spectral reflectance goes up quickly with vivid young shoots. In summer, the increasing ratio drops down and begins to decrease. On the other hand, red spectral reflectance value arrive the maximum. It is the season of red leaves. After this season, it becomes winter and vegetation stops the activities till early spring.

The periodicity of spectral reflectance of vegetation become more evident by modifying Figure 1 and developing the red band value and infrared band value on the two dimensional coordinate as shown in Figure 2. The change of spectral reflectance of vegetation is greater in infrared band rather in red band. Also as for season, the change will be revealed greater in spring and autumn season rather in summer and winter.

3. RELATIONSHIP BETWEEN THE PERIODICITY OF LANDSAT AND SEASONAL DIAGRAM OF JAPANESE

It seems that the periodicity of LANDSAT data, every 18 days it returns back to the beginning orbit, is a very meaningful properties to survey the signature of land patterns or land changes in connection with season.

Season has been defined by divide a year into 24 equal periods in Japan. Each dividing point is called seasonal datum point and has special name suitable for each season as shown in Figure 3. These seasonal points have the base line which connect the summer solstice point and the winter solstice point and cycle in order. The meaning of the seasonal points name are as described in Table 1.

Having sensed the change in mountains or fields, people has plowed so long periods from ancient age under this seasonal diagram. The interval of seasonal datum points is about 15 days. This interval seems convenient unit to make clear the transition of seasonal change.

Today, when LANDSAT data were used for monitoring the status of crops or vegetation by remote sensing technique, such diagram seems useful. The time interval of LANDSAT covering same place is a problem when utilizing the data by such time serial forms.

The periodicity of 18 days is close to the interval of 15 days of seasonal periods. If clear LANDSAT data were acquired every 18 days, they would become very timely and useful data for tracing and monitoring the seasonal phenomena specially of vegetation on the fields.

4. PROBABILITY OF SEASONAL DATA ACQUISITION

The probability of obtaining every seasonal multi-spectral data by LANDSAT is related with clear days of the local area and the month. If the LANDSAT data were acquired always every 18 days, it would be expected that LANDSAT MSS data almost corresponding to 24 seasonal datum points could be acquired.

However in actual, there are not so many time when clear day meets with the just LANDSAT covering day. The clear day is defined as the day of climate status of less 25% cloudiness over the whole sky. Monthly and local statistics of clear days is as shown in Table 2.

If the LANDSAT data of less 25% cloudiness were effective, the probability obtaining one data per month will be gotten by multiplying the number $1/18$. For example, the probable time in Tokyo local area is $3.7/18 = 0.2$ on April and $5.0/18 = 0.3$ on May. Also, if 3 LANDSAT satellites were orbited at the same time and the data could be obtained every 6 days, the probability of one data acquisition per month will be expected to about 60% on April and 90% on May.

5. COMPOSITION OF MULTI-SEASONAL DATA

The flow to compose the multi-seasonal data from four seasonal LANDSAT MSS data is shown as Figure 4. Among the all LANDSAT data acquired in a past year, sufficient data required for seasonal data analysis should be selected. Each LANDSAT data is composed of four multi-spectral scanner data. One band is designated in the four data for each season, then combination data containing four seasonal information will be produced.

This data-set is called multi-seasonal data in this paper. An example shown in Figure 4 is a multi-seasonal data of the 6th band. Such a seasonal-spectral signature will be obtainable for vegetation in the temperate zone. A big problem to compose the multi-seasonal data is the registration. Any pixel of every seasonal scene must be matching with an identical ground objective point always.

6. REGISTRATION OF LANDSAT IMAGES

LANDSAT data taken in different time have some differences of the location by each scene. These data can not be matched with easily. The desirable accuracy of registration for multi-seasonal data analysis is less one pixel. Two methods of registration as shown in Figure 5 are created by using the Image-100 system and used.

Method 1: Interactive methodA method to make registration interactively on the CRT images. Two temporal images are displayed on CRT by red and green ones. Using the objectives which is clearly identified as the boundary, i.e. shoreline or river, the parallax appearing on two images were eliminated and superimposed closely. For eliminating the parallax, a function is added to the system which moves a figure left to right in parallel or rotates it. On a small part of full LANDSAT scene, about 10 km square, any scene is almost similar and the scale is equal too, consequently a sufficient registration can be performed.

Method 2: Utilizing LANDSAT MAP system.....An essential and accurate registration method. LANDSAT MAP means the rearranged form of LANDSAT MSS data or the processed results which are completely compatible with the national topographical map.

For making LANDSAT MAP, Ground Control Points (GCP) are used. The GCP can perform the accurate correspondence with the topographical map. Searching a point which can be clearly identified both on the topographical map and on the LANDSAT image, then a function which connect with both coordinate values is determined.

In above method, the procedure is divided into two parts through interim coordinate values of the Universal Transversal Mercator's projection (UTM).

Step 1: Topographical coordinate----UTM coordinate.

Step 2: UTM coordinate----Coordinate (pixel/line) on the LANDSAT image.

In the use of these transformation formula, the accuracy of location is nearly $\pm 40m$ in practice.

7. CLASSIFICATION OF ENVIRONMENT BY MULTI-SEASONAL DATA

If the reflectance values of two different seasons were plotted on two-dimensional signature space as shown in Figure 6, they would make their separated clusters as well multi-spectral data do so. In order to classify the environment by multi-seasonal LANDSAT data, the same method in multi-spectral data handling can be applied. Two methods are as follows:

Method 1: Interpretation of composite false color photographs----A method to make a false color composite from different seasonal data and then to interpret the environmental signature through the color change, the tone or the patterns.

Method 2: Application of digital analysis of multi-spectral data----This method is an application of the numerical analysis of multi-spectral data. In RESTEC (Remote Sensing Technology Center of Japan), there exist two methods, one is the Multi-Categorical Analysis method attached in the M-DAS system, another is the Single-Cell Signature Acquisition or Multi-Cell Signature Acquisition method attached in the Image-100 system.

8. QUALITY INVESTIGATION OF PADDY FIELD BY 3 SEASONAL LANDSAT DATA (EXAPMLE-1)

As first trial of multi-seasonal data analysis, it has been intended to make clear a characteristics of paddy fields from three seasonal data, spring, summer and autumn ones. The test area was decided to the enclosed area as shown in Figure 7. Figure 8 shows the displayed scenes on the Image-100 by each band of LANDSAT MSS data corresponding to this area. Each displayed frame contains the spring, summer and autumn scene in order from top to bottom.

From the MSS 4th band scene, a special phenomenon along the shoreline are recognized. As for this, two estimations are considered. One is an interpretation that the bottom of the lake appears because water level had been down. Another is an interpretation that some kinds of vegetation, probably Brazilian Waterweed, increased in early spring and the color of water-surface changed.

Also two facts are known from the 7th MSS band data. In spring scene, the color is black near shoreline, on the other hand, it turns whitish as far away from the shoreline to the east-south-east direction. The black appearance of lakeside shows that the area is moist and the white appearance near Notogawa station shows the growing vegetation in early spring which reflects stronger spectral energy of IR band. Quancity of vegetation in this place is less than ones in the banks of the River Echi.

It turns white all over the rice fields in the summer scene. When autumn comes, rice plants are reaped. In the bottom scene of Figure 9 on October 24th, Dainakanoko polder area looks like white as shown contrary to the spring scene. This is due probably to a fact that the rice fields dried up and the surface appears white or due to a fact that new shoots of rice plants had grown up again after the harvest, then the reflectance of IR spectral band comes stronger up.

The Middle scene of Figure 9 is one which has been displayed by superimposing each seasonal data of the 7th MSS band and making to a composite color which consists of green, blue and red corresponding to each spring, summer and autumn scene.

In order to survey the further details of those signatures on rice fields, this scene was categorized to some groups by M-DAS. It was executed by utilizing a multi-seasonal data which was composed of spring, summer and autumn MSS 7th band data. The data format is made to be the same form of the LANDSAT CCTs.

Training areas were selected as shown in Table 3. The results of categorized area is shown also on Table 3. The categorization accuracy is listed in Table 4 and seems enough. The distribution of categorized groups corresponding to Table 3 appears on Figure 10. A fact is known that Dainakanoko polder paddy field, Notogawa paddy field and Ogawa paddy field are different typed ones each. The features change as far away from the lakeshore to the inland.

In addition to this multi-seasonal data analysis, three results categorized from each seasonal data were shown as Figure 11.

9. PROGRESS CHECK OF PADDY FIELD BY 3 LANDSAT DATA IN HARVEST SEASON (EXAMPLE-2)

In this section, an example of the analysis by using the temporal spectral data nearly corresponding to seasonal datum points. This trial was executed by 3 time serial data acquired on September 11th, October 5th and October 24th as shown in Figure 12. This season seems suitable for surveying the rice condition and the harvest estimation. Time intervals of each data are about 20 days, although these data do not belong to a same year. By making a composite color from three data, the process of rice harvest becomes clear.

In a scene on September 11th, so big color differences do not appear between on the banks of the River Echi and on the rice fields, but the green of the banks comes up extremely in the data on October 5th.

A composite color which was made from each temporal scene by giving blue, green and red color in order of the seasonal sequence shown on the middle of Figure 13. Paddy fields show bluish and a east-half area of Dainakano-ko polder where the harvest had probably not yet finished at that time on October 5th shows whitish. Contrary to this, banks of the river or mountains show green.

Analyzing the multi-seasonal data at the middle of Figure 13 by the Multi-Categorical Processor of the M-DAS, Table 7 is obtained. Five training areas were chosen. For the purpose to clarify the differences of the harvest period, an early harvesting paddy field is drawn by yellow and a later harvesting paddy field is done by yellow-green as shown in Figure 14. The accuracy of categorization performance is just shown in Table 6 and seems to be enough. Uncategorized area could be counted still up to about 34%. However, it is known that these places have spreaded concentrically on the river and the banks.

10. DETAILED SURVEY OF VEGETATIONAL ENVIRONMENT BY SUMMER AND WINTER LANDSAT DATA (EXAMPLE-3)

There have been published so far the number of reports dealing with vegetational environment by using LANDSAT data. Almost the reports, however, have been ones which had been analyzed by single-seasonal data by itself. Therefore, supposing multi-spectral data acquired in winter, the analyzed results refer only to a vegetational distribution in the winter season. It does not mean that vegetational environment has been grasped enough.

In order to know the vegetational distribution as possible as accurate and to grasp the vegetational environment properly, some multi-spectral data acquired in different seasons should be composed and analyzed to the meaningful categories. In this example, using LANDSAT data of Tokyo area, the detailed distribution of evergreen trees, deciduous trees and grass fields were investigated in two cases. One is a case of single-seasonal data. Another case is of double-seasonal data.

Used data and analysis system : Both LANDSAT data acquired on December 1972 (winter data) and on July 1976 (summer data) were chosen as the objective data for this study. As for analysis system, the M-DAS was used.

In order to register both scenes accurately and also to make easy the correspondence between LANDSAT picture elements and ground objective locations, a couple of topographical-map (scaled 1:25,000) compatible LANDSAT MSS data was compiled by rearranging LANDSAT pixels.

The effect of utilization of the new arrayed LANDSAT CCT (called LANDSAT MAP temporally) was proved to exist in availability of the speedy correspondence against the ground data acquired by interpretation of color aerial photograph or ground truth surveying, rather in convenience of the superimposing procedure itself. The project area illustrated is shown in Figure 15.

Flow of the study : As the first approach, a fairly detailed classification on vegetational ground coverage was done by using summer and winter data respectively. Next, in order to compose a double-seasonal MSS data from single-seasonal MSS data as shown in Figure 16, number of spectral bands which seems to be influenced by the seasonal change of vegetational environments was determined.

Figure 16 show the concept of assembling the double-seasonal MSS data. Extracting each two channels from summer and winter data respectively, assembled data was made into the same form of ordinary LANDSAT CCT format. Same classification procedure was taken for this data as well for single-seasonal MSS data also, and the results was compared and evaluated with the first stage ones.

Categories of classification are sea, inland water, factories, densely build-up area, residential lots and vegetation. As for vegetation, further detailed classification was conducted. The categories were divided into lawn, grass fields, evergreen trees on grass field, deciduous trees on grass field, forest of evergreen trees, forest of deciduous trees and the mixed place.

For the purpose of easy allocation of the training areas for vegetational division, 3 times expanded LANDSAT data of Yoyogi park area was made. Training areas given for each category of vegetation were designated by referring to the classification draft of Figure 17 which had been created by comparing the-spot-ground surveyed data with the aerial photograph of Yoyogi park scaled 1 to 8,000 shown in Figure 18.

Evaluation of the results : In M-DAS system, the classification results are displayed pixel by pixel on the Moving Window Display (MWD) by specified colors for each group. Figure 19-a and Figure 19-b are both the winter MSS data displayed on the MWD by a false color rendition. Figure 20-a and Figure 20-b are the classified results corresponding to the false colored picture displayed on the MWD also.

Figure 21 is a classification map arranged from Figure 20-b. When reviewing this map, the number of deciduous trees are misclassified to residential lots or densely build-up area. This is probably caused by the reason why there are smaller vegetation mass in actual. The grass land is in a withered condition and the reflectivity of the place is so high that the distribution of grass land has been well distinguished (Place A in Figure 17). On the other hand, there are some misclassified areas in the region where many tall buildings are concentrated because the sun elevation is low.

Spectral signature of those categories in the winter images are shown as Figure 22. Those curves were obtained by calculating statistically the training group data designated through the M-DAS operation.

Spectral reflective energies are rather small on whole categories, since influenced by the low sun elevation. In almost categories except vegetation, the longer the wavelength, the smaller the reflective energy. The reflectivity of evergreen trees has a tendency to be smaller than ones of deciduous trees or grass land. Specially, reflective response of the 5th band appears small.

Comparing increase and decrease of the features in the winter data, the main characteristics valuable for the classification seems to be in the 5th, 6th and 7th band.

Figure 23-a and Figure 23-b are both the summer MSS data displayed on the MWD by a false color rendition. Figure 24-a and 24-b are the classified results corresponding to the pictures. The classified map arranged from Figure 24-b is as Figure 25.

An advantage of vegetational classification by summer data is that the boundary between the large-mass area of vegetation, such as the forest of the Meiji shrine, and the place where there are a little or almost no vegetation as the Shinjuku town, was delineated clearly than the results of winter data. Nevertheless, small parks or lots with a small vegetation are often missing and categorized into the residential area of suburbs or densely build-up area, probably because the quantity of greens does not reach a level.

Classified results in the place where clouds cast the shadows are not good (Place B). Also, in regard to the identification between evergreen trees and deciduous trees, some misclassified regions are recognized (Place C).

Figure 26 is a spectral signatures of each category obtained from summer data. On the contrary to winter data, reflection energy becomes higher wholly. The variation becomes greater in every band and it is much specially in the 7th band. Comparing both data of town and suburbs, the value of suburbs is higher, because there are more vegetation among their garden in suburbs rather in town and reflectance energy of IR spectral band comes higher.

Evergreen trees was divided into two types, broad leaved ones and needle leaved ones. It is known that the difference in both 7th bands is undistinguishable from Figure 26. As for grass land and deciduous trees, the energy difference is smaller in the 7th band rather in the 6th band. Consequently, remarkable bands of summer data are proved to be the 5th and 6th band. Integrating above all two cases, the bands which are characteristic to both winter and summer data are determined to 5th and 6th band.

In order to get a detailed classification of vegetation, the 5th band and the 6th band were selected for double-seasonal data source, then they were assembled as shown in Figure 16. Using this assembled double-seasonal spectral data, categorization procedure was conducted.

Results were shown in Figure 27-a and 27-b. Figure 28 was compiled from Figure 27-b. This distribution status of vegetational environments is almost close to ones in actual. It is also known that well classification can be done even in the rather small vegetation area where misclassification had sometimes occurred in the single-seasonal data. Most of those small greens are small public gardens. Vegetational components of those area are mixed trees of evergreen and deciduous ones or rather deciduous trees. As for inland water, the better separation was gotten than winter case as seen in the Palace side creeks.

Short summary : It is confirmed that better solutions can be obtained when using suitable double-seasonal data for the purpose of surveying the vegetational environments by LANDSAT data. In case of the survey of detailed vegetational environment, it is difficult to do completely by only single-seasonal MSS data. On the contrary, in case of using suitable double-seasonal spectral data composed of 5th and 6th band each, it is easy to perform the separation among evergreen trees and deciduous trees or the mixed ones. That is, very similar results to actual one seems to be obtained.

Vegetational environment of Tokyo, as shown in Figure 27-a, is better in the west side where much residential lots are, than in the east side where many streets or factories exist.

11. CALCULATION OF RECLAMATION AREA 1972 TO 1976 BY LANDSAT 1 AND 2 DATA (EXAMPLE-4)

By using two LANDSAT scenes both covering Tokyo district on December 14th, 1972 and on July 29th, 1976, the scope and distribution of lands which were reclaimed along the shoreline of Tokyo Bay in this period are investigated. Time interval is changed from seasonal one to far long one, about four years in this application. This analysis is considered to be an extension of the multi-seasonal data analysis. Process of the study is as follows:

At first, accurate registrations were conducted by some ground control points. Next, a composite spectral data was reproduced from each LANDSAT MSS data by extracting the 5th and 6th band.

Reclamation areas were identified on this data through a technique of Single-Cell Signature Acquisition of the Image-100 (Single-Cell Method). The 5th and 6th band are decided by following reason. The biggest difference of spectral value appears in the 6th band in order to distinguish land from water. In addition, the 5th band which is in visible range and less influenced by atmospheric conditions was chosen.

Whole view of reclaimed area in Tokyo Bay : The first step to know the scope and distribution of reclaimed area in Tokyo Bay is to expand the LANDSAT MSS image on the Image-100. The size of display monitor of the Image-100 is 512 x 512 pixels. If one pixel is taken to 100 m sq. 51.2 km sq. area appears on the CRT surface. The outer frame of Figure 29 shows the range. Both displayed images of LANDSAT 1 and 2 corresponding to the frame are shown in Figure 30. The coordinate values for the four corners are listed in Table 8. Two images had been produced to be superimposed with maximum error of one pixel.

After extracting the 5th and 6th band from each MSS data and processing them by the Single-Cell Method, orange parts come up as reclaimed land as appearing in Figure 31. Number of orange pixels is 2419 and this is equivalent to 24.19 km². Spectral ranges corresponding to orange parts are 14-24 (MSS 5 of LANDSAT 1), 4-16 (MSS 6 of LANDSAT 1), 68-118 (MSS 5 of LANDSAT 2) and 58-114 (MSS 6 of LANDSAT 2) by each.

Partial view of reclaimed area in Tokyo Bay : Above display is not enough to know the detailed distribution of the reclaimed area or to calculate the area. For this purpose, it had better to make an enlarged scene. Here, the enlarged scenes were made by adjusting a pixel size so as to become 20 m sq., equivalent to 0.04 ha. Whole image on the Image-100 becomes 10.24 km sq..

Choosing 8 divisions where reclamation had been progressed in Tokyo Bay, each enlarged image of LANDSAT 1 and 2 was produced. The 8 divisions were shown in Figure 29 and coordinate values of each four corners were listed in Table 8. Also the distribution of reclaimed area is recognized by the green alarm shown in Figure 29. The spectral signature is in Table 9.

Spectral values of LANDSAT 1 are relatively small because those areas had been sea surface at that 1972. After reclamation, the spectral reflectance turns to ones proper for soils or rocks and takes very high values.

Though saying simply it is reclamation in general, there exists already completed ones, and also now constructing ones, too. Spectral reflectance is like of soils with grass or like of concrete surface in completed reclamation area. On the contrary, it is inclined to be lower in constructing ones because some places were drawn under water.

Therefore, when various reclamation lands are involved in a same division, it is difficult to fulfil the theme extraction by only an operation. In such case, according to the condition

of reclamation, a few of Single-Cell Method should be applied for each characteristic reclamation and they should be summed up. For example, in Edogawa division, the analysis was conducted for three kinds of reclamation. Specified color for these are pink, yellow and ochre as shown in Figure 29.

Accuracy of area calculation : The degree of accuracy about the distribution and calculated area of reclaimed lands obtained through above procedure was estimated by following comparison.

Each division with the green alarm of reclamation on the CRT of the Image-100 was taken on slide films. These films were projected on the topographical map scaled 1 to 50,000. All reclaimed lands appearing on these films were traced under some adjustment and the area was measured planimetrically. The results is shown at most right column of Table 9.

After comparing those values with ones obtained from Single-Cell Method, the differences were listed up and known to be about 0.4 sq-km. These seem to be the things which show the performance of Single-Cell Method. It is considered that these differences do not depend on the scale of the reclaimed area but on the frame size itself, 512 x 512 pixels here. Then it had better to say that classification error is 0.8% per a frame.

Grand total of reclaimed area in Tokyo Bay is proved to be 33.8 km² by Single-Cell Method and also 33.4 km² by planimetry.

12. CONCLUSION AND PROSPECT

Technical problems of multi-seasonal data analysis are summerized to following points:

1. Possibility of timely data acquisition.
2. Degree of accurate registration for multi-seasonal data.

The possibility of timely data acquisition depends almost on weather only. Number of clear days with 25% less cloud is different in regions. When viewing all regional data of Japan, clear days are considered to be about 20 to 60 days and have seasonal deviations besides. As for Tokyo district, on the contrary to 12.3 days per month on January, average number of clear days from June to August reaches merely 1.3 days per month. Such small statistics of the clear days means that it is very difficult to acquire the LANDSAT data of the season. However, it is considered that summer seasonal data fulfil very important roles in order to investigate the vegetational environments. Then, if it were desired to increase the probability of data acquisition in this season, more LANDSAT satellites would become the solution.

As for accurate registration among seasonal LANDSAT data, the best way is considered to use the LANDSAT data in the form of the LANDSAT MAP which reproduced from raw LANDSAT CCT by ground control points in order to superimpose accurately to the national topographical map.

Referring to ground truth for multi-seasonal data analysis, the data related to this is very few. Variations of spectral reflectance with respect to various vegetation should be measured through a year in various regions. It remains as a future study that in what fields the multi-seasonal data analysis will be effective. In this report, four examples have been shown but these are a little part of the possibility. Multi-seasonal data analysis will have many applications specially in the field related to vegetation.

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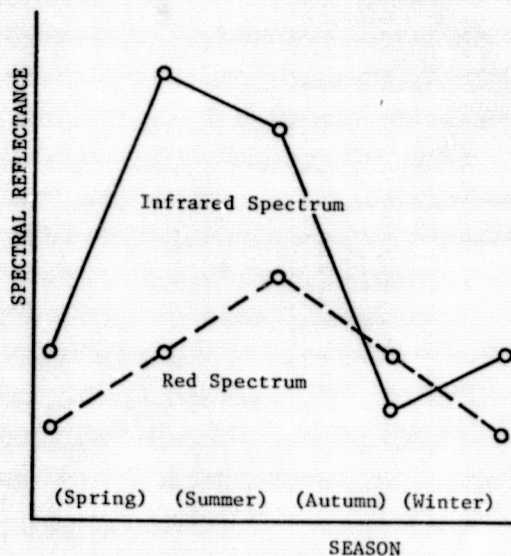


Figure 1. A seasonal change of spectral reflectance of vegetation

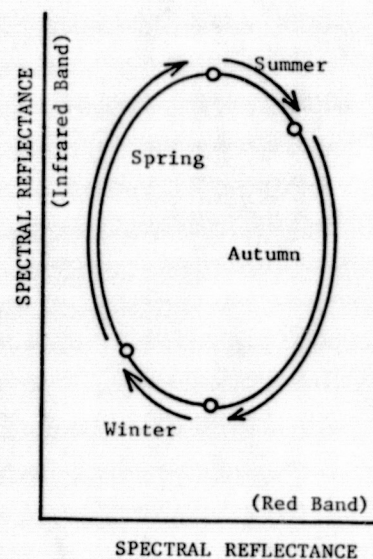


Figure 2. A hysteresis loop of spectral reflectance of vegetation

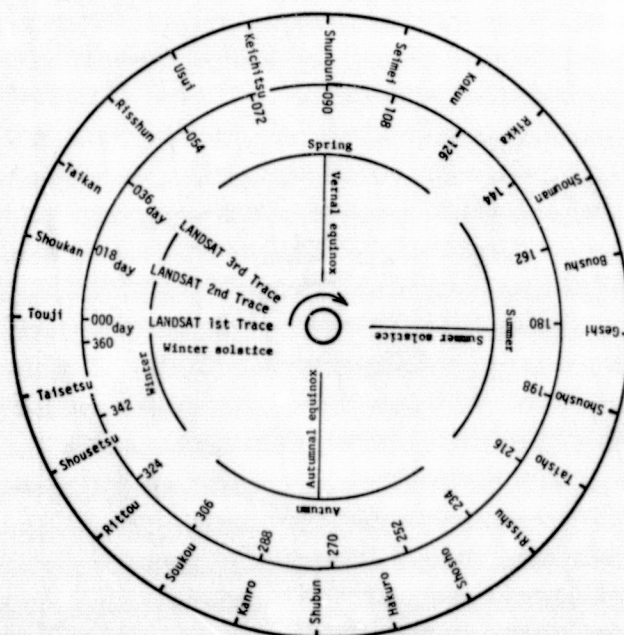


Figure 3. Seasonal datum points and repeatability of LANDSAT

No.	Name	Date	Meaning
1	Rishun	Feb 04	the setting-in of spring
2	Usui	Feb 19	rain rather than snow
3	Keichitsu	Mar 06	wintering worms crawl out
4	Shunbun	Mar 21	the vernal equinox
5	Seimei	Apr 05	clear and bright season when trees and plants begin to put for the young shoots
6	Kokuu	Apr 20	rain for crops
7	Rikka	May 06	the first day of summer
8	Shouman	May 21	fields and mountains become full of vegetation
9	Boushu	Jun 06	sow the seeds of arestae
10	Geshi	Jun 22	the summer solstice
11	Shousho	Jul 07	the second hottest season
12	Taisho	Jul 23	the hottest season
13	Rishu	Aug 08	the setting-in autumn
14	Shosho	Aug 23	end of hot season
15	Hakuro	Sep 08	white dew
16	Shubun	Sep 23	the autumnal equinox
17	Kanro	Oct 09	cold dew
18	Soukou	Oct 24	frost
19	Rittou	Nov 08	the first day of winter
20	Shosetsu	Nov 23	light snow
21	Taitsetsu	Dec 07	heavy snow
22	Touji	Dec 22	the winter solstice
23	Shoukan	Jan 06	the second coldest season
24	Taikan	Jan 20	the coldest season

Table 1. Meanings of Japanese seasonal points name

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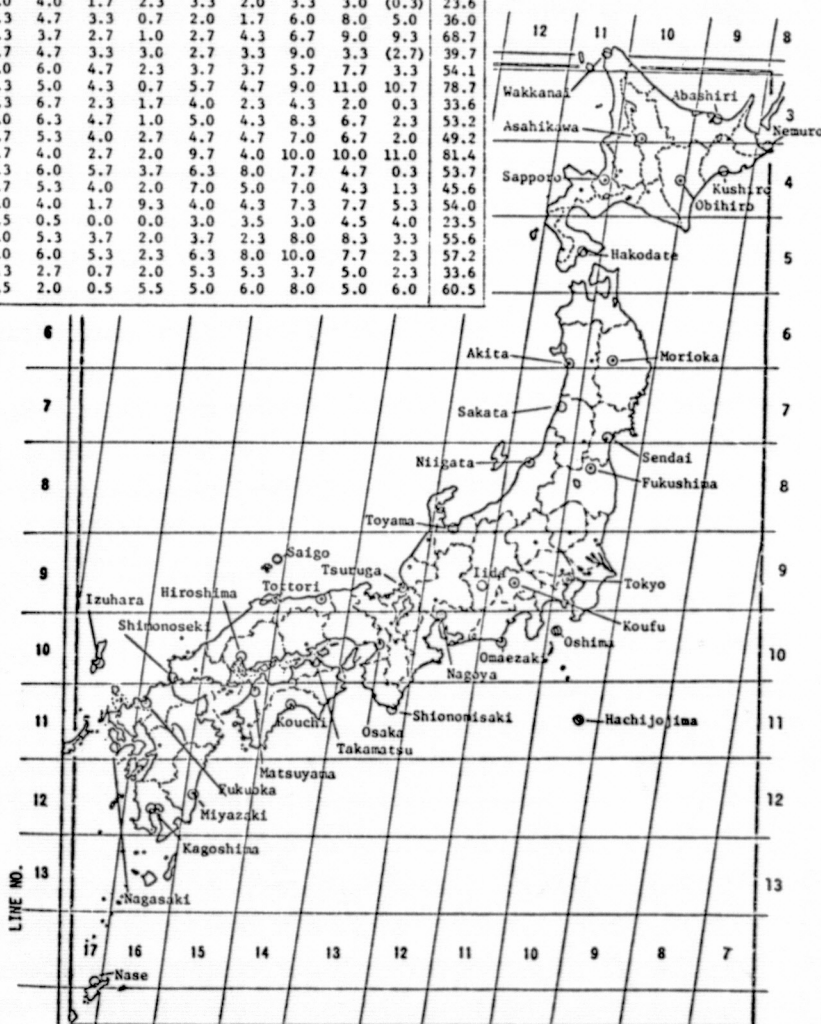
Course No.	Place	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
8	Nemuro	(7.3)	(7.7)	(4.7)	(3.3)	1.0	0.7	0.0	0.0	2.7	8.7	4.7	(8.0)	17.8
9	Abashiri	(2.3)	(3.0)	(1.7)	(4.7)	1.0	2.3	2.3	0.7	5.3	5.0	(2.7)	(5.7)	16.6
9	Kushiro	(14.7)	(9.7)	(7.0)	(4.3)	1.0	0.3	0.0	1.7	1.3	8.7	9.0	(12.3)	22.0
10	Asahikawa	(1.3)	(1.7)	(3.0)	(5.7)	1.7	4.0	1.0	1.3	3.3	4.7	(0.7)	(0.3)	16.0
10	Obihiro	(12.7)	(13.7)	(7.3)	(5.0)	1.7	2.0	0.7	1.0	3.3	8.3	8.7	(11.3)	25.7
10	Morioka	(1.3)	(1.3)	(1.7)	3.0	4.3	1.3	0.0	0.7	1.3	5.0	3.3	(1.3)	18.9
10	Sendai	(5.0)	(4.3)	(3.7)	5.0	6.0	3.0	1.7	2.3	2.0	4.7	5.3	(2.7)	30.0
10	Fukushima	(3.0)	(3.3)	(3.7)	4.3	6.3	2.0	1.7	3.0	1.0	4.3	3.3	(2.7)	25.9
10	Tokyo	12.3	6.7	6.0	3.7	5.0	1.3	1.3	1.3	1.7	4.3	6.3	8.0	57.9
10	Oshima	11.3	4.7	6.0	4.0	3.0	1.7	1.0	1.3	2.3	4.7	6.0	10.7	56.7
10	Hachiojima	2.0	0.0	1.7	3.3	2.0	0.7	1.0	1.7	3.3	2.7	3.7	2.7	24.8
11	Wakkanai	(0.0)	(0.7)	(3.3)	(4.7)	0.7	2.0	1.7	2.3	4.7	4.3	(1.7)	(0.0)	15.7
11	Sapporo	(1.3)	(1.7)	(2.0)	(5.3)	2.3	2.3	2.0	1.3	4.3	6.3	(2.0)	(1.3)	18.5
11	Hakodate	(1.3)	(2.3)	(2.3)	5.0	2.3	3.0	1.3	2.3	4.0	7.0	2.7	(0.0)	27.6
11	Akita	(0.0)	(0.0)	(0.7)	1.3	2.7	2.7	2.7	1.3	3.0	3.3	2.0	(0.0)	19.0
11	Sakata	(0.0)	(0.0)	(0.7)	2.0	3.0	4.0	5.0	2.3	2.7	1.7	1.7	(0.3)	22.4
11	Niigata	(0.0)	(0.0)	(1.3)	2.7	6.0	3.0	2.3	2.3	2.3	2.3	1.7	(0.3)	22.6
11	Koufu	14.3	9.7	8.0	4.7	4.7	1.3	0.0	0.3	0.7	6.3	8.7	13.3	72.0
11	Omaezaki	15.7	9.3	7.7	4.3	2.7	2.5	0.7	0.7	2.3	5.0	9.3	14.3	74.5
12	Toyama	(0.7)	(0.7)	(3.0)	3.7	5.0	2.0	1.0	2.3	1.0	3.7	2.3	(0.0)	21.0
12	Iida	(9.3)	(7.0)	(6.7)	4.3	5.3	2.7	0.3	0.3	0.7	4.7	6.0	6.0	30.3
12	Nagoya	6.3	7.0	7.7	4.7	7.0	4.0	1.0	3.7	3.0	9.0	7.0	8.7	59.1
12	Tsuruga	(0.7)	(1.0)	(2.3)	4.0	4.0	1.7	2.3	3.3	2.0	3.3	3.0	(0.3)	23.6
13	Osaka	6.0	5.3	6.0	6.3	4.7	3.3	0.7	2.0	1.7	6.0	8.0	5.0	36.0
13	Shionomisaki	11.7	8.0	6.3	3.3	3.7	2.7	1.0	2.7	4.3	6.7	9.0	9.3	68.7
14	Tottori	(0.7)	(0.3)	2.0	4.7	4.7	3.3	3.0	2.7	3.3	9.0	3.3	(2.7)	39.7
14	Takamatsu	4.7	3.3	6.0	3.0	6.0	4.7	2.3	3.7	3.7	5.7	7.7	3.3	54.1
14	Kouchi	12.3	6.3	4.7	4.3	5.0	4.3	0.7	5.7	4.7	9.0	11.0	10.7	78.7
15	Saigo	(1.3)	(0.7)	2.7	5.3	6.7	2.3	1.7	4.0	2.3	4.3	2.0	0.3	33.6
15	Hiroshima	2.3	3.0	5.3	4.0	6.3	4.7	1.0	5.0	4.3	8.3	6.7	2.3	53.2
15	Matsuyama	2.0	2.7	3.7	3.7	5.3	4.0	2.7	4.7	4.7	7.0	6.7	2.0	49.2
15	Miyazaki	11.3	8.7	4.3	3.7	4.0	2.7	2.0	9.7	4.0	10.0	10.0	11.0	81.4
16	Shimonoseki	1.7	1.3	4.0	4.3	6.0	5.7	3.7	6.3	8.0	7.7	4.7	0.3	53.7
16	Fukuoka	1.3	2.0	3.7	2.7	5.3	4.0	2.0	7.0	5.0	7.0	4.3	1.3	45.6
16	Kagoshima	4.0	3.7	4.0	3.0	4.0	1.7	9.3	4.0	4.3	7.3	7.7	5.3	54.0
16	Naha	0.0	0.5	1.0	3.5	0.5	0.0	0.0	3.0	3.5	3.0	4.5	4.0	23.5
17	Izuhara	6.0	4.3	4.7	4.0	5.3	3.7	2.0	3.7	2.3	8.0	8.3	3.3	55.6
17	Nagasaki	1.0	2.3	3.0	3.0	6.0	5.3	2.3	6.3	8.0	10.0	7.7	2.3	57.2
17	Nase	1.3	1.0	2.0	2.3	2.7	0.7	2.0	5.3	5.3	3.7	5.0	2.3	33.6
17	Ishigakijima	15.0	0.5	1.5	5.5	2.0	0.5	5.5	5.0	6.0	8.0	5.0	6.0	60.5

Table 2. The number of days per month with 25% or less cloud cover for local areas.

Note 1. This list is statistics by Monthly Report of the Japan Meteorological Agency (1967 to 1969).

2. () shows the month when snow covers the ground more than 7 days.

Note : These numbers were assigned by the Science and Technology Agency of Japan in order to inform easily the location of any LANDSAT scene to the researchers.



Course numbers and line numbers for LANDSAT data in Japan.

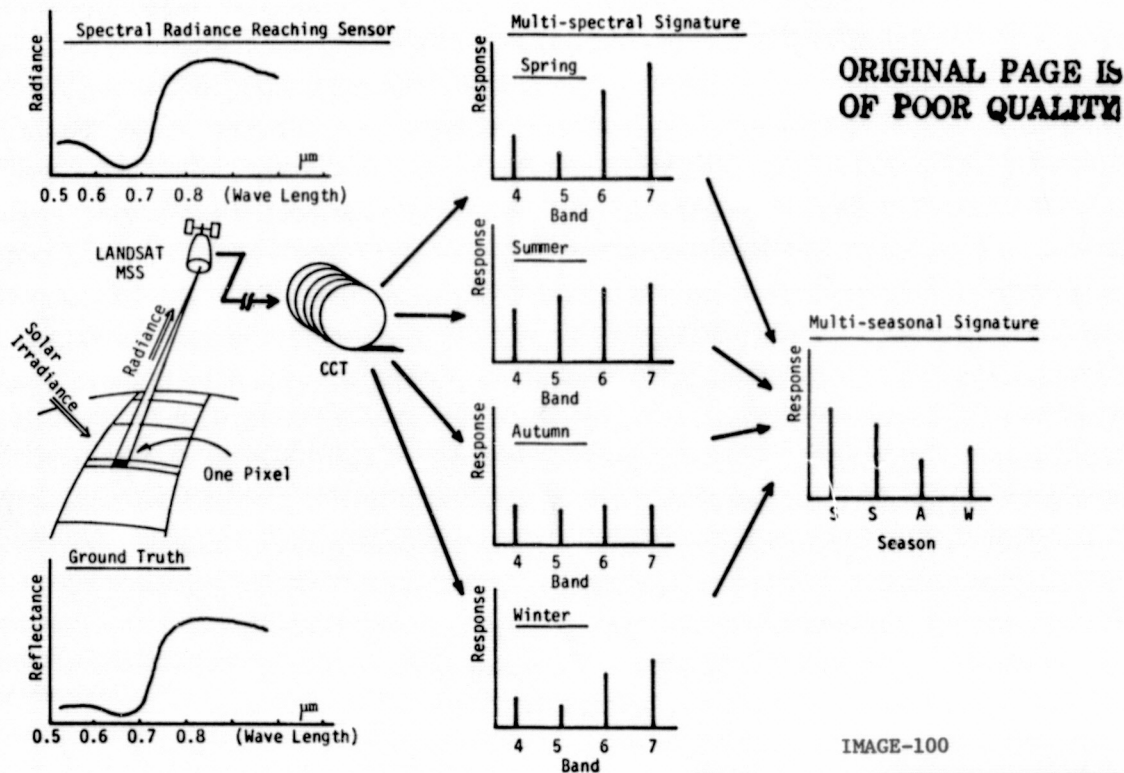


Figure 4. Composition of Multi-Seasonal Data

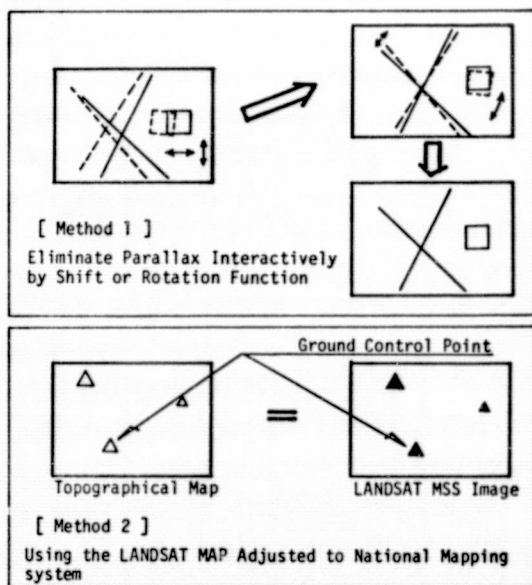


Figure 5. Registration of LANDSAT Image

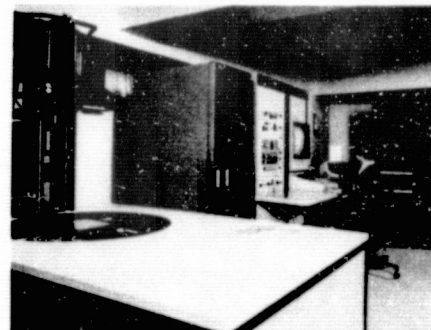


IMAGE-100

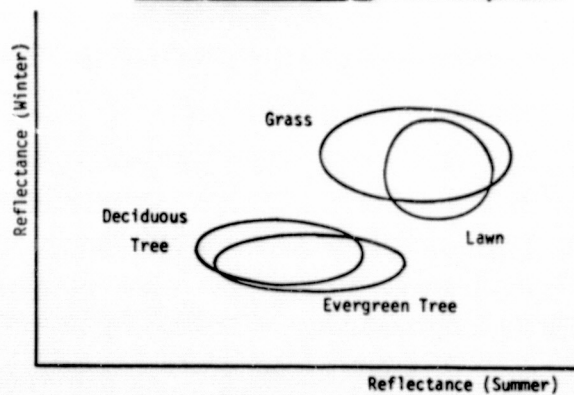


Figure 6. Two-seasonal signature space

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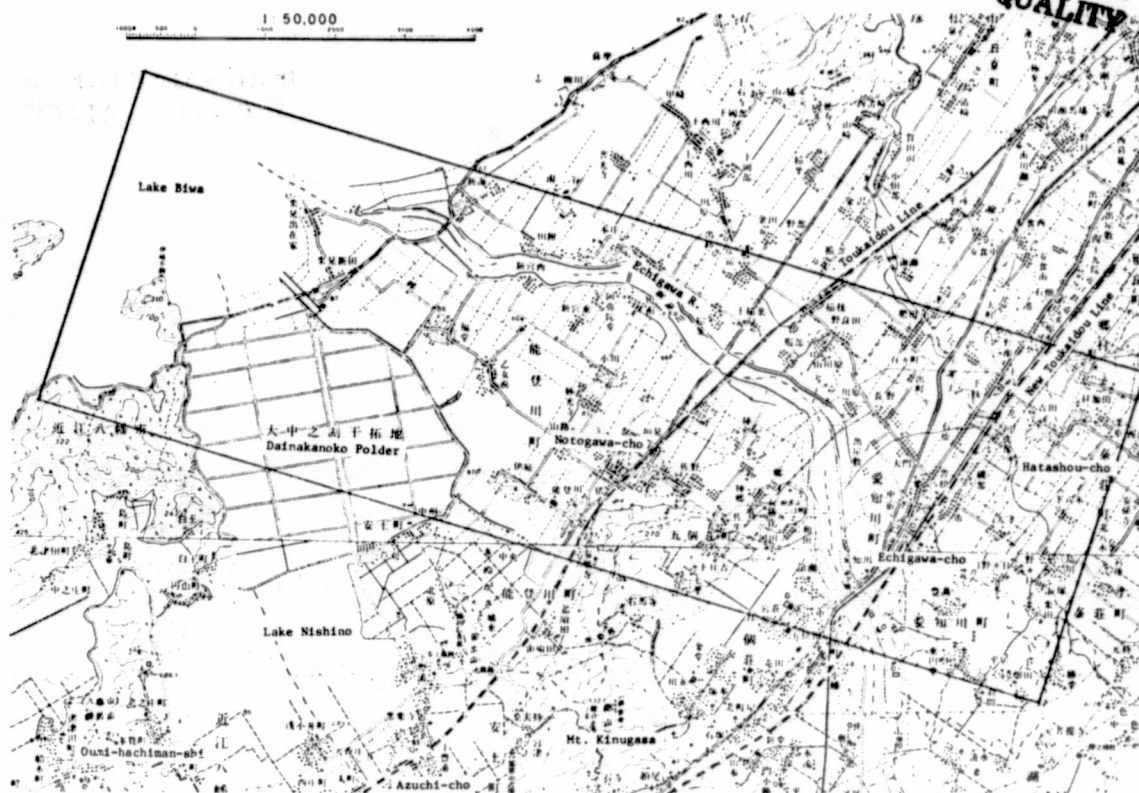
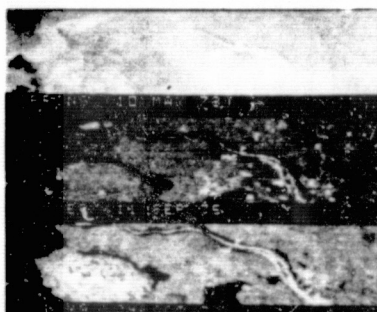
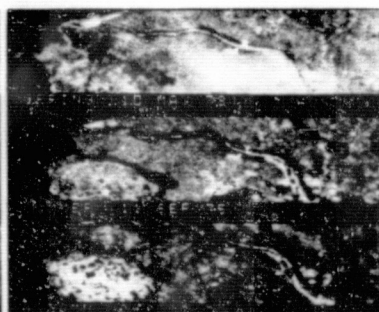


Figure 7. Investigated field at BIWA lake side (5km X 15km)



MSS 4



MSS 5

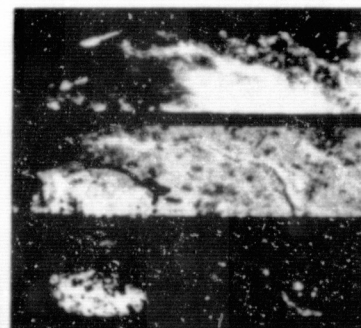
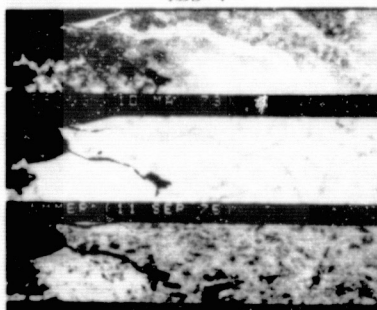
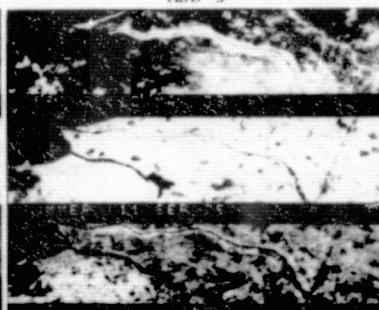


Figure 9. Simply superimposed
color [middle frame]



MSS 6



MSS 7

Figure 8. Multi-Seasonal LANDSAT raw data
[Spring + Summer + Autumn]

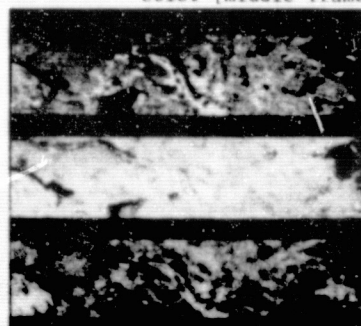


Figure 12. Repeated LANDSAT
scene about 20 days interval

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DN	GN	COLOR	NOB	X1	Y1	X2	Y2	X3	Y3	X4	Y4	NAME
0	0	000										
1	1	070	624	1747	279	1771	274	1772	304	1756	314	DAINAKANOKO POLDER
2	2	050	441	1792	229	1812	224	1817	251	1798	251	NOTOGAWA SUIDEN
3	3	770	209	1845	242	1872	234	1872	244	1845	252	OGAWA SUIDEN
4	4	500	244	1885	290	1912	275	1920	288	1894	293	NOTOGAWA T.
5	5	037	143	1809	277	1817	277	1834	284	1819	292	LAKE BIWA
6	6	040	315	1889	302	1925	296	1925	305	1889	313	KINUGASA MT.
7	7	003	837	1625	193	1657	193	1657	221	1625	221	LAKE BIWA
8	8	040	115	1866	208	1889	210	1899	220	1866	211	HONJOY(BAMBOO)

Table 3. Training area Allocation [Ex.-1]

TNG SET	0	1	2	3	4	5	6	7	8
1	4	87	7	2	0	0	0	0	0
2	0	3	87	9	0	0	0	0	0
3	0	0	9	91	0	0	0	0	0
4	2	0	0	0	97	0	0	0	1
5	3	0	0	0	0	88	0	9	0
6	10	0	0	0	3	0	77	0	11
7	3	0	0	0	0	0	0	97	0
8	0	0	0	0	3	0	3	0	94

Table 4. Categorization performance [Ex.-1]

GRP NO.	CATEGORY	NOB	PERCENT OF TOTAL	SQ. KM
0	UNCATEGORIZED	7794	21.69	8.82
1	DAINAKANOKO POLDER	5274	14.68	5.97
2	NOTOGAWA SUIDEN	5413	15.06	6.12
3	OGAWA SUIDEN	4958	13.80	5.61
4	NOTOGAWA TOWN	2166	6.03	2.45
5	LAKE BIWA	975	2.71	1.10
6	KINUGASA MT.	2823	7.86	3.19
7	LAKE BIWA	4596	12.79	5.20
8	HONJOY(BAMBOO)	1935	5.38	2.19
TOTAL		29602	100.00	40.64

Table 5. Results of categorized area by MCP Method [Ex.-1]

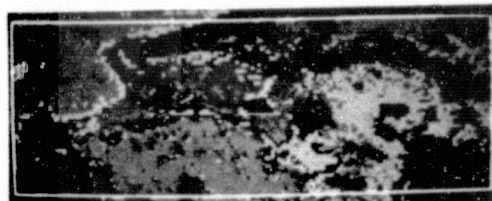
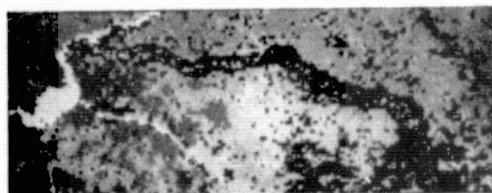
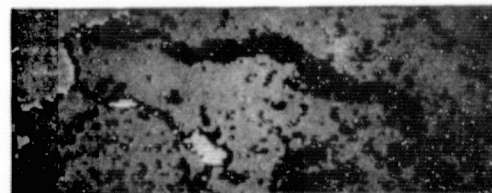


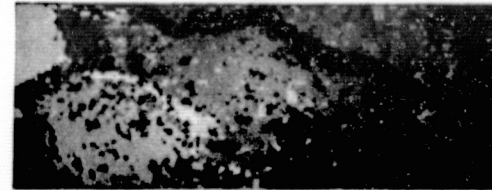
Figure 10. Color display of categorized area [Ex.-2]



Spring



Summer



Autumn

Figure 11. Each categorization for three seasons



Figure 13. Superimposed image of 3 MSS data [middle frame]

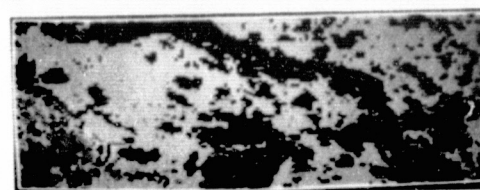


Figure 14. Categorized area displayed by M-DAS

TNG SET	0	1	2	3	4	5
1	3	95	2	0	0	0
2	1	0	98	0	0	0
3	4	0	0	96	0	0
4	5	0	0	0	95	0
5	5	0	0	0	0	95

Table 6. Categorization performance [Ex.-2]

GRP NO.	CATEGORY	NOB	PERCENT OF TOTAL	SQ. KM
0	UNCATEGORIZED	12004	34.89	13.58
1	DAINAKANOKO POLDER	2049	5.95	2.32
2	NOTOGAWA SUIDEN	16796	48.81	19.00
3	NOTOGAWA TOWN	1320	3.84	1.49
4	LAKE BIWA	408	1.19	0.46
5	KINUGASA MT.	1836	5.34	2.08
TOTAL		31126	100.00	38.92

Table 7. Calculated categorized area [Ex.-2]



Figure 15. Study area [Ex.-3]

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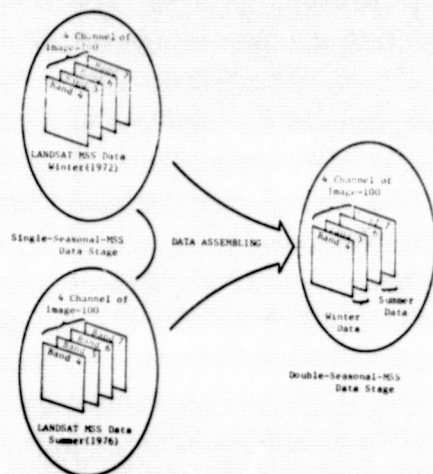


Figure 16 an Illustration of Data Assembling for Vegetation Environment Analysis



Figure 18. Color aerial photograph for interpretation

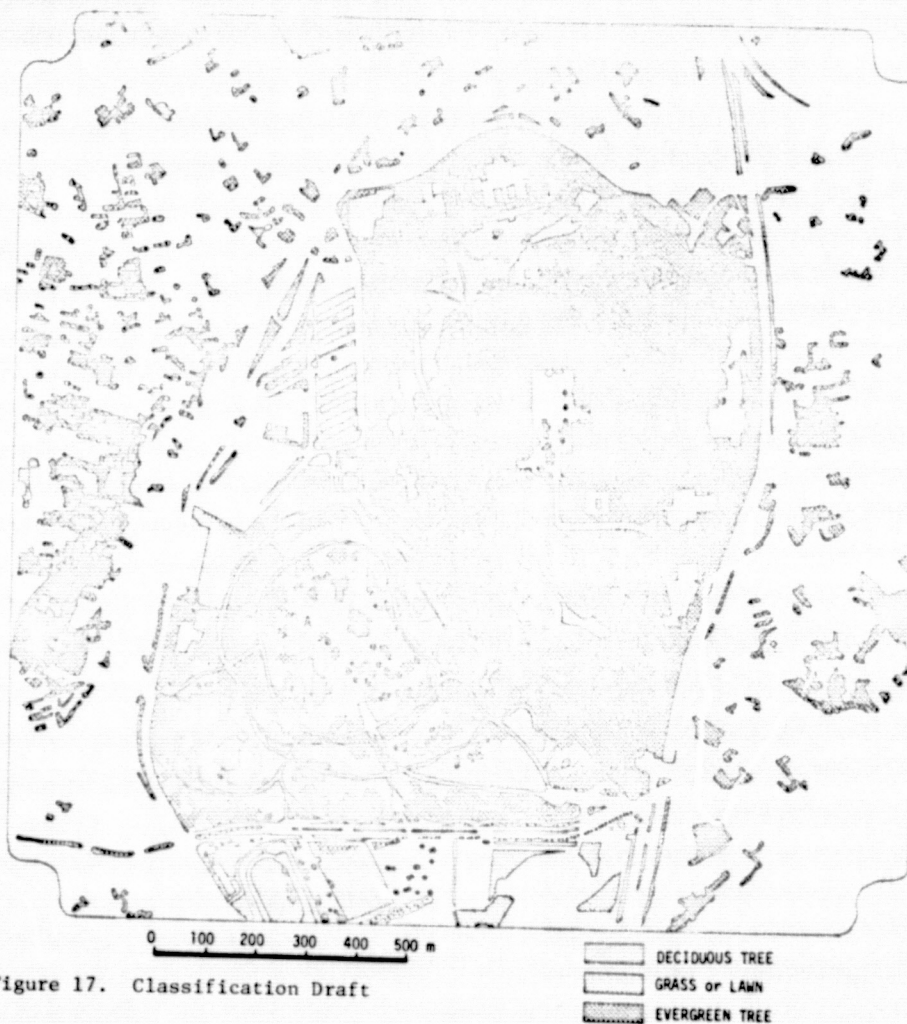


Figure 17. Classification Draft

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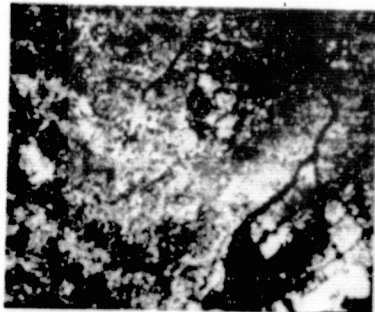


Figure 19-a. False Color
rendition of winter data

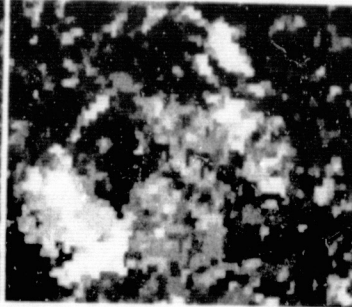


Figure 19-b. False color
rendition of winter data[x3]

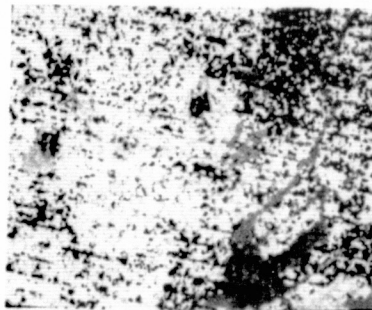


Figure 20-a. Classification
products of winter data



Figure 20-b. Classification
products of winter data[x3]

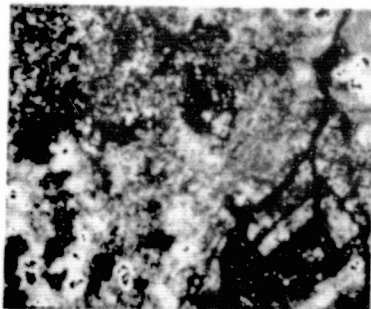


Figure 23-a. False Color
rendition of summer data

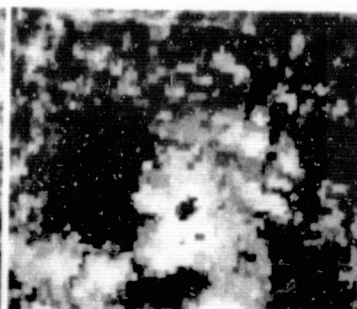


Figure 23-b. False color
rendition of summer data[x3]

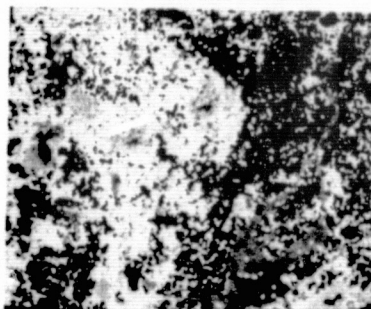


Figure 24-a. Classification
products of summer data

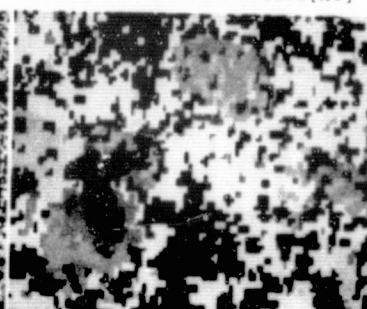


Figure 24-b. Classification
products of summer data[x3]



Figure 21. Arranged Results on Vegetation Area
A: Forest of Evergreen tree
B: Forest of Evergreen tree & Deciduous tree
C: Forest of Deciduous tree
D: Evergreen tree & Background grass
E: Deciduous tree & Background grass
F: Grass
G: Lawn

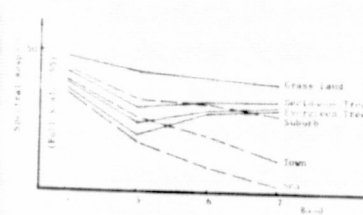


Figure 22. Typical Spectral Response of Each Category
from the Winter LANDSAT Data

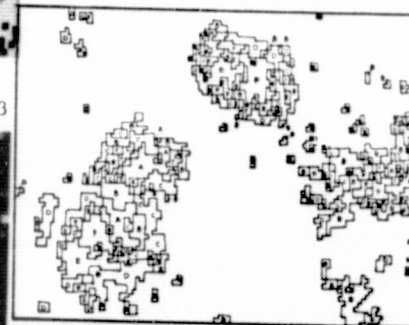


Figure 25. Arranged Results on Vegetation Area
A: Forest of Evergreen tree
B: Forest of Evergreen tree & Deciduous tree
C: Forest of Deciduous tree
D: Evergreen tree & Background grass
E: Deciduous tree & Background grass
F: Grass
G: Lawn

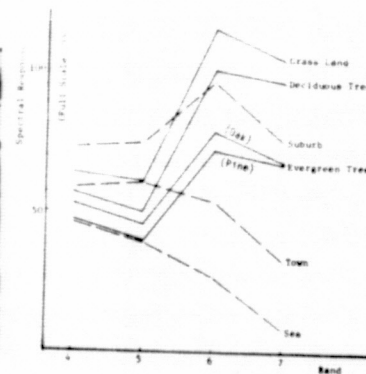


Figure 26. Typical Spectral Response of Each Category
from the Summer LANDSAT Data

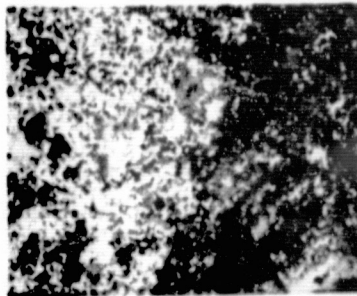


Figure 27-a. Classification from double-seasonal data

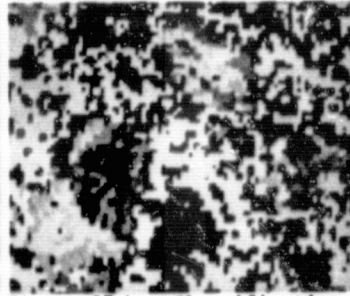


Figure 27-b. Classification from double-seasonal data

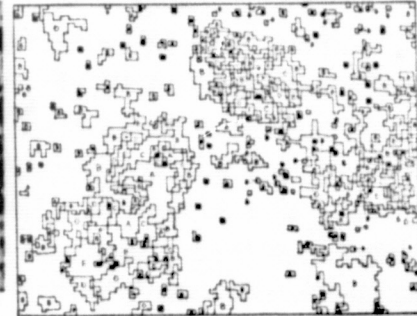


Figure 28 Arranged Results on Vegetation Area
A: Forest of Evergreen tree
B: Forest of Evergreen tree & Deciduous tree
C: Forest of Deciduous tree
D: Evergreen tree & Background grass
E: Deciduous tree & Background grass
F: Grass
G: Lawn

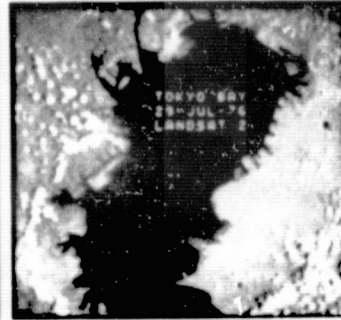
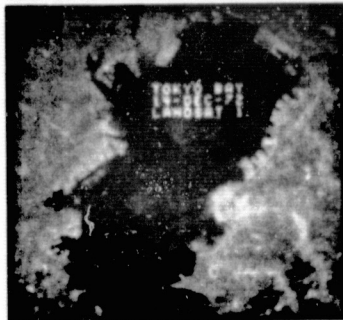


Figure 30. Tokyo Bay in 1972 and 1976 by the Image-100



Figure 31. Reclamation around Tokyo Bay

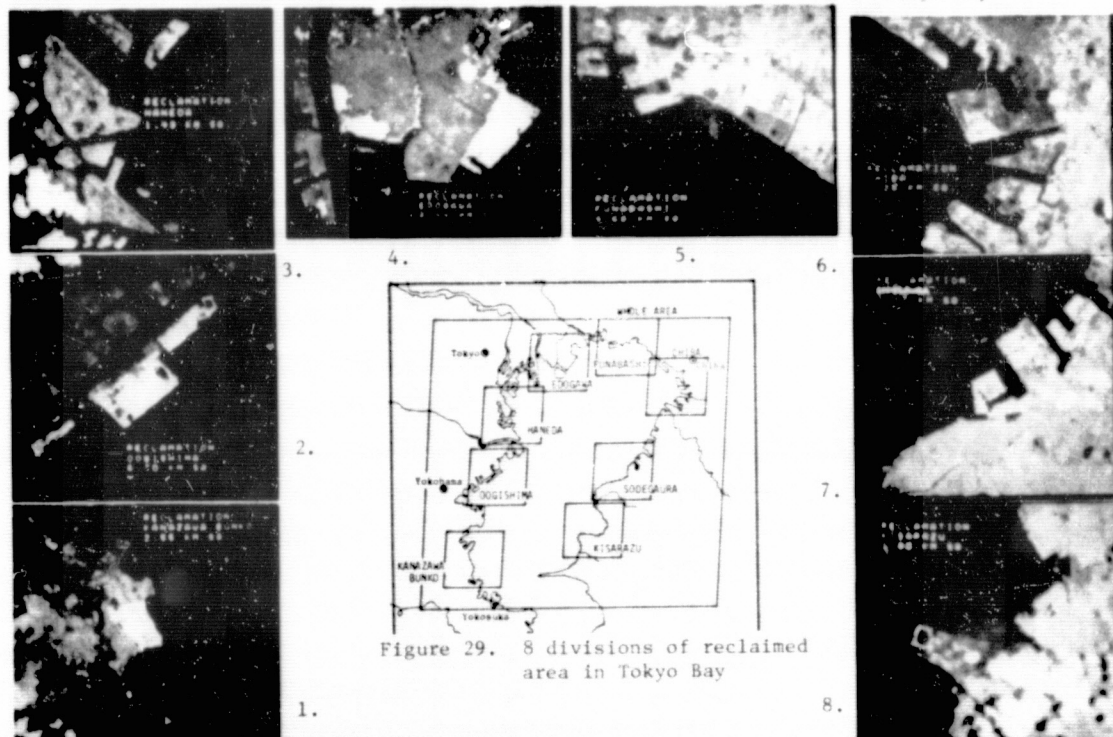


Figure 29. 8 divisions of reclaimed area in Tokyo Bay

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Name of Site	No.	LANDSAT I		LANDSAT II		Ground Coordinates Values			
		Pixel	Line	Pixel	Line	X ^m	Y ^m	Latitude	Longitude
Full Scene of Tokyo Bay	001	921.7	1513.2	952.0	1693.0	-27983.9	-15149.6	35 44 51.4	139 39 56.8
	002	1813.2	1516.5	1849.0	1693.0	-37774.0	35402.2	35 39 31.8	140 13 27.7
	003	928.7	2155.4	952.0	2340.0	-78157.0	-27675.6	35 17 42.1	139 31 44.4
	004	1820.0	2158.6	1849.0	2340.0	-87947.1	22876.2	35 12 24.9	140 05 01.6
1. KANAZAWABUNKO	101	996.2	1984.9	1022.0	2168.0	-65582.9	-20400.7	35 24 30.9	139 36 11.2
	102	1174.1	1985.5	1201.0	2168.0	-67536.5	-10312.9	35 23 28.0	139 43 11.2
	103	997.5	2112.9	1022.0	2297.0	-75586.5	-22898.1	35 19 06.0	139 34 53.2
	104	1175.3	2113.5	1201.0	2297.0	-77540.1	-12810.3	35 18 03.2	139 41 32.8
2. OOGISHIMA	201	1057.0	1799.5	1085.0	1981.0	-51769.1	-13229.9	35 31 59.6	139 41 14.7
	202	1234.8	1800.2	1264.0	1981.0	-53722.8	-3142.1	35 30 56.5	139 47 55.2
	203	1058.2	1927.6	1085.0	2110.0	-61772.7	-15727.3	35 26 34.8	139 39 36.2
	204	1236.1	1928.2	1264.0	2110.0	-63726.4	-5639.5	35 25 31.8	139 46 16.3
3. HANEDA	301	1097.3	1658.8	1127.0	1839.0	-41215.8	-8113.8	35 37 42.3	139 44 37.4
	302	1275.2	1659.4	1306.0	1839.0	-43169.4	1974.0	35 36 39.0	139 51 18.4
	303	1098.6	1786.8	1127.0	1968.0	-51219.4	-10611.2	35 32 17.6	139 42 58.6
	304	1276.4	1787.4	1306.0	1968.0	-53173.0	-523.4	35 31 14.4	139 49 39.2
4. EDOGAWA	401	1222.4	1544.1	1254.0	1723.0	-33606.4	1289.3	35 41 49.4	139 50 51.2
	402	1400.2	1544.8	1433.0	1723.0	-35560.1	11377.1	35 40 45.7	139 57 32.5
	403	1223.6	1672.1	1254.0	1852.0	-43510.0	-1208.2	35 36 24.7	139 49 11.9
	404	1401.5	1672.8	1433.0	1852.0	-45563.7	8879.6	35 35 21.2	139 55 52.7
5. FUNABASHI	501	1419.8	1515.1	1453.0	1693.0	-33451.9	13085.0	35 41 54.1	139 58 40.5
	502	1597.7	1515.7	1632.0	1693.0	-35405.6	23172.8	35 40 50.0	140 05 21.7
	503	1421.1	1643.1	1453.0	1822.0	-43455.5	10587.6	35 36 29.5	139 57 0.7
	504	1599.0	1643.7	1632.0	1822.0	-45409.2	20675.4	35 35 25.5	140 03 41.4
6. CHIBA	601	1579.7	1601.0	1611.0	1779.0	-41845.4	20324.4	35 37 21.2	140 03 27.8
	602	1755.5	1601.6	1790.0	1779.0	-43799.1	30412.2	35 36 16.9	140 10 08.5
	603	1578.9	1729.0	1611.0	1908.0	-51849.0	17826.9	35 31 56.8	140 01 47.7
	604	1756.8	1729.6	1790.0	1908.0	-53802.7	27914.7	35 30 52.5	140 08 28.0
7. SODEGAURA	701	1426.5	1786.0	1457.0	1966.0	-54666.0	8025.1	35 30 25.8	139 55 18.5
	702	1604.3	1786.6	1636.0	1966.0	-56619.6	18112.9	35 29 21.9	140 01 58.7
	703	1427.7	1914.6	1457.0	2095.0	-64669.6	5527.7	35 25 01.2	139 53 39.1
	704	1605.6	1914.6	1636.0	2095.0	-66623.2	15615.5	35 23 57.4	140 00 18.9
8. KISARAZU	801	1343.3	1918.7	1372.0	2100.0	-64129.6	640.6	35 25 18.8	139 50 25.3
	802	1521.2	1919.3	1551.0	2100.0	-66083.3	10728.4	35 24 15.2	139 57 05.2
	803	1344.6	2046.7	1372.0	2229.0	-74133.2	-1856.9	35 19 54.1	139 48 46.4
	804	1522.5	2047.3	1551.0	2229.0	-76086.9	8230.9	35 18 50.6	139 55 25.9

Table 8. Coordinate values for four corners of each reclaimed site

NAME OF SITE	Satellites	Spectral MSS 5			Spectral MSS 6			Pixels	Calculated Area		Difference
		Bounds	Mean	Var.	Bounds	Mean	Var.		Method-1	Method-2	
The Whole Area of TOKYO BAY	LANDSAT I LANDSAT II	14- 24 17.1 68-118 90.8	1.3 54.3	1.3 54.3	4- 16 8.2 58-114 89.7	1.3 57.2	1.3 57.2	2419			
KANAZAWABUNKO	LANDSAT I LANDSAT II	14- 20 16.7 64-114 86.2	1.9 94.2	1.9 94.2	6- 12 8.9 56-114 83.9	2.8 148.2	2.8 148.2	6378	2.55	2.62	-0.07
OOGISHIMA	LANDSAT I LANDSAT II	18- 28 22.2 66-128 93.6	4.5 139.3	4.5 139.3	8- 18 12.5 68-124 88.2	3.9 115.6	3.9 115.6	16742	6.70	8.40	-1.70
HANEDA	LANDSAT I LANDSAT II	18- 26 22.5 56- 94 85.0	2.8 49.4	2.8 49.4	8- 14 10.1 48-100 87.0	3.7 50.0	3.7 50.0	3570	1.43	1.30	0.13
EDOGAWA (Ocher) (Yellow) (Pink)	LANDSAT I LANDSAT II	18- 26 22.6 52- 68 59.2	2.1 4.9	2.1 4.9	4- 20 12.4 36- 58 48.5	1.5 9.4	1.5 9.4	21102 9338	8.44	7.10	1.34
	LANDSAT I LANDSAT II	20- 28 24.6 58- 82 69.0	1.2 11.6	1.2 11.6	8- 20 13.9 56- 84 70.1	1.2 21.5	1.2 21.5	6023			
	LANDSAT I LANDSAT II	28- 34 32.0 64-100 78.9	1.5 30.3	1.5 30.3	16- 24 20.6 56- 98 71.3	0.6 37.4	0.6 37.4	5741			
	LANDSAT I LANDSAT II	12- 22 16.7 48- 98 74.3	1.1 53.0	1.1 53.0	4- 12 7.0 30-124 75.4	1.0 108.7	1.0 108.7	23952	9.58	9.27	0.31
CHIBA	LANDSAT I LANDSAT II	14- 20 16.5 38- 74 58.6	0.6 35.3	0.6 35.3	4- 8 6.8 30- 70 52.5	0.9 37.4	0.9 37.4	2803	1.12	0.40	0.72
SODEGAURA	LANDSAT I LANDSAT II	20- 28 23.3 54- 98 66.8	1.1 49.7	1.1 49.7	8- 16 11.4 44- 98 62.1	0.9 66.3	0.9 66.3	5419	2.17	1.97	0.20
KISARAZU	LANDSAT I LANDSAT II	20- 28 24.1 54- 80 68.6	1.1 18.5	1.1 18.5	8- 16 11.7 44- 88 62.5	1.4 24.7	1.4 24.7	4496	1.80	2.29	-0.49
								Total:	33.79	33.35	

Remarks 1. Spectral data range is 0-255.

2. Method-1: Cell Method Method-2: Geometrical measurement Method

Table 9. Calculated area of each reclaimed site

DIGITAL EXPLOITATION OF SYNTHETIC APERTURE RADAR

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ABSTRACT

A digital processing and analysis scheme for use with digitized synthetic aperture radar data has been developed. Using data from a four-channel system, the imagery is preprocessed using specially designed software and then analyzed using pre-existing facilities originally intended for use with MSS type data. Geometric and radiometric correction may be performed if desired, as well as classification analysis, Fast Fourier transform, filtering and level slice and display functions. The system provides low cost output in real time, permitting interactive imagery analysis. System information flow diagrams as well as sample output products are shown.

1. INTRODUCTION

A multi-channel Synthetic Aperture Radar (SAR) system has recently been developed at ERIM [1]. As with a conventional multispectral scanner (MSS), the purpose of multichannel radar is to obtain more information about the surface of the earth than might otherwise be possible with a single channel system. With multichannel radar imagery each channel interacts with the roughness of target surfaces in a different way to produce different degrees of diffusivity (hence intensity of reflection back to the antenna) and depolarization. These differences aid in image interpretation. Existing analysis techniques used with MSS data can be successfully applied to SAR data [2]. There are, however, several inherent problems with SAR data that must be considered and in most cases corrected before digital exploitation techniques can be effectively utilized. These problems are due, in part, to SAR's unique geometry and to its data collection procedure.

This paper discusses a software system which has been specifically designed to process multichannel SAR data interactively. The package contains provisions to correct for geometric and relative radiance distortions inherent in the SAR data. These include conversions of geometry based on slant to ground range corrections, displaced nadir, antenna radiation pattern and R^4 power losses. Provisions are also made to provide for spatial registration of the four data channels produced by the SAR.

Once the preprocessing and corrections have been performed, the software package permits display of the imagery, level slicing, histogramming, densitometry scans and signature analysis. These can be done interactively in real time using a Tektronix graphics display terminal or as hard copy using a CALCOMP plotter, line printer or color ink jet printer.

The processing software is resident on the University of Michigan Terminal system, a large multiprocessing system capable of simultaneously supporting batch operations and more than 150 interactive terminals. This system uses an AMDAHL 470 central processing unit under a University of Michigan designed operating system. The processing software is capable of generating magnetic tapes that are compatible with the ERIM-ARIES [3] (RADAR) and MIDAS (MSS) [4] exploitation facilities.

2. BACKGROUND

The software package described in this paper was a modification of the University of Michigan LIGMALS/H processing system. The modification was implemented through the use of a series of add on modules. LIGMA/H is a modular interactive processing package designed for real time processing of MSS data [5]. The LIGMALS/H architecture permits the modification and expansion of system capabilities through the use of simple program modules. This approach permits maximum flexibility during the development and testing of various processing algorithms.

The SAR data used in this study was obtained from the ERIM multichannel radar. This is a dual wavelength-dual polarization SAR system that simultaneously images at X-band (3.2 cm) and L-band (23.5 cm) wavelengths.

Alternate X- and L-band pulses (either horizontally or vertically polarized) are transmitted and reflections of both polarizations received; thus four channels of radar imagery are simultaneously obtained. Both polarizations of X-band are recorded on one film and both polarizations of L-band on another.

Previously, with a SAR capable of imaging with a single-wavelength at any one time, successive passes were required for multiple wavelength images. This constraint causes problems in image gathering and interpretation, particularly if a significant length of time intervenes between the imaging passes. Because of simultaneous imaging, multiplexed SAR imagery has several advantages: identical imaging parameters for each wavelength (radar look direction, depression angles, etc.), the same imaged swath, the same motion errors, and the same terrain conditions (surface texture, slope orientations, vegetation, etc.). Also, multiplexed SAR imagery is easier to machine-process because image registration is simplified.

The rationale for using a digital computer as opposed to photographic products for image analysis is two-fold; digital coding permits the storage of data with a very large dynamic range and facilitates the use of automated processes for target identification and analysis. Although radar sensors frequently operate with a range of return brightnesses spanning 60 dB, most photographic emulsions can only record intensities with a dynamic range of 17-20 dB with a linear response. Further, because of brightness compressions associated with this nonlinear response pattern, many gradational details in image can be lost due to "lumping" of brightness levels at the extreme bright and dark ends of the response window. The wide dynamic range capabilities of CCT's makes it possible to store images of this sort without loss or compression of brightness details. Further, digital computers can be programmed to perform supervised and unsupervised target recognition and classification processing on radar data stored in CCT form.

The data was digitized using the ERIM hybrid optical-digital processor [3]. This facility exploits the optical correlation for the computations necessary to reduce the signal film to an image. It presents the full dynamic range of the radar, by digitizing the image at the output plane with an image dissector. The data, digitized to 256 grey levels, was recorded on computer compatible magnetic tape (CCT's).

3. SYSTEM DESCRIPTION

Figure 1 illustrates the flow of data through the ERIM/RADAR digital data processing system. Basically, optically processed SAR data is digitized on the ERIM image dissector facility. The output CCT (800 BPI) from this procedure is then run through a modular pre-processing stack that can perform one or all of the following pre-processing algorithms:

- 1) Slant to Ground Range conversion
- 2) Antenna radiometric corrections

- 3) R^4 power loss correction, and
- 4) Four-channel registration.

The operational details of these four pre-processing algorithms are outlined in Figure 2.

Once the data has been pre-processed, it can be interactively exploited in real time using the LIGMAL/H digital processing and display system. Exploitation algorithms include the ability to:

- 1) Level slice
- 2) Ratio two channels
- 3) Subtract two channels
- 4) Histogram, and
- 5) perform densitometry.

Pre-processed data (i.e., geometrically and radiometrically corrected) can alternately be played back through the ERIM image dissector facility to produce film imagery output.

In addition to the above mentioned exploitation algorithms other changes have been incorporated into this system to more effectively handle SAR data. These include a two-dimensional Fast Fourier Transform algorithm and a moving window smoothing (low pass filter) and integration algorithm (low pass filter) which is designed to decrease the amount of coherent speckle without significantly reducing image resolution. These functions are shown in Figure 1 in dashed outlines, indicating that they are still undergoing testing and modification at the present time.

Exploited data can be displayed at this point on the RAMTEK (ARIES) facility or displayed in real time using a remote Tektronix Terminal. The Tektronix terminal is used for graphical and statistical displays as well as interactive generation of gray tone images. Hard copy of Tektronix displayed data is produced on a CalComp plotter. The three data products available on the CalComp plotter are:

- 1) X-Y plots (histograms and brightness)
- 2) gray tone images
- 3) 3-color images.

Gray map using a seven-character representation are also available. These appear on standard computer print out paper (44.5 cm wide).

Additional interface software has been developed to permit communication of the radar imagery to the ERIM/MIDAS processing facility for use with its high speed classifier and ink jet printer output facility. Figure 3 provides an example of MIDAS output using the ink jet printer. This image is a false color composite image of a portion of the intercoastal waterway near Marineland, Florida. It covers an area of approximately 2.5 km². In this image, the returns of various radar channels were used to inversely modulate the flow of subtractive primary colored dyes, i.e., the greater the return in a given channel, the less dye was applied to the output product at the corresponding location. The channels used and their associated colors were:

- X-Band, horizontally polarized - MAGENTA
- X-Band, cross polarized - YELLOW
- L-Band, horizontally polarized - CYAN

Initial investigations indicate that a multichannel composite image of this sort provides much greater utility for the interpreter than single channel gray tone images of the same channels. Extreme care must be taken to insure proper registration between channels or the image produced will produce false artifacts and be very difficult to interpret. This procedure can also be used with multi-

temporally obtained radar imagery to produce land cover change detection, assuming proper registration between images can be maintained. This may involve rotations and "rubber sheet" stretching to provide the best possible fit between passes.

4. CONCLUSIONS

The use of a modular system allows the flexibility to add special purpose software programs to the LIGMALS system more efficiently. The real time interactive Tektronix terminal allows users to analyze data quickly.

Further, the approach taken, wherein pre-existing processing systems were utilized with only minor modifications permits the implementation of the new processing scheme with a minimal investment in new software and hardware systems. By pre-processing the SAR data to be compatible with pre-existing systems, most changes in approach can be implemented in the pre-processing stages rather than through major modifications in the processing system.

Preliminary results indicate that the use of this digital processing scheme permits more detailed analyses to be performed on imagery. Such processes as signature analysis and recognition, ratio processing, level slicing and multi-channel compositing have been successfully performed, indicating that this data can be handled in very much the same way as MSS data. One caveat does, however, exist in the analysis of these images. The sensor geometry differs in a radar system from a standard MSS system such that care must be taken in the analysis of an image or the application of a processing algorithm or erroneous results can be generated.

5. REFERENCES

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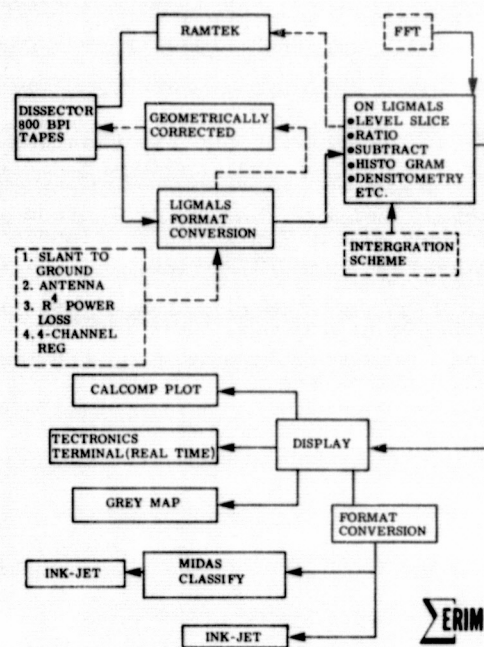


FIGURE 1

Flow Chart of Format Conversion Preprocessing Program

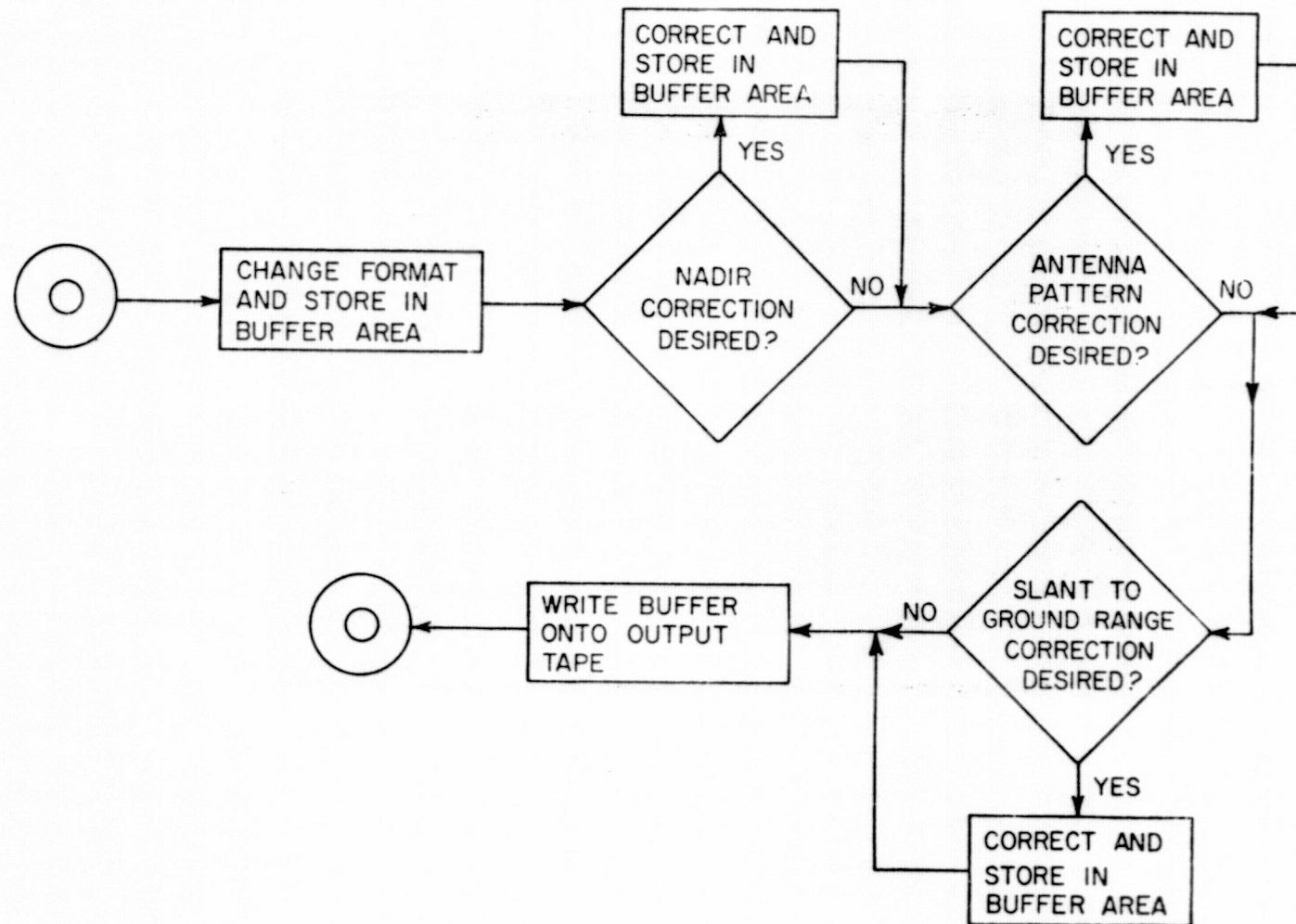


FIGURE 2

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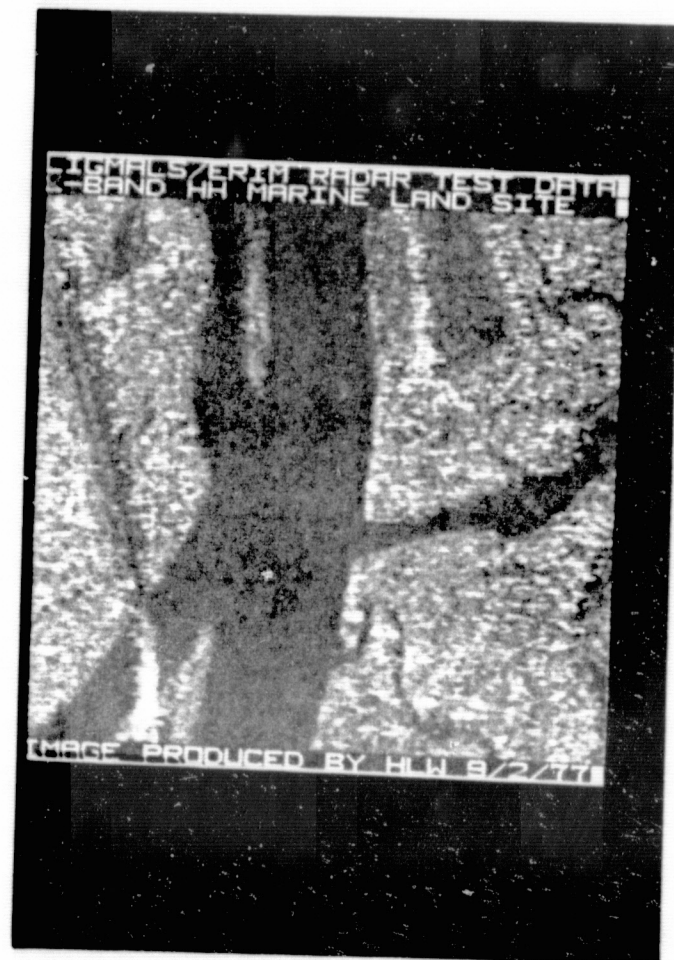


FIGURE 3

ON THE PHOTOGRAPHIC PROCESSING AND
DIGITAL TEXTURE FOR
REMOTE SENSING OF KUJUKURI COAST OF CHIBA IN JAPAN

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ABSTRACT

Remote sensing of various coastal phenomena on the Kujukuri Coast and Kashimanada Coast has been done by use of aircraft for the purpose of investigating the characteristics of shore reefs and floating sand, and the depth of the sea. A multispectral camera and a video ITV camera have been used as sensor. The first flight was over the Kashimanada and Kujukuri Coasts and the next flight was over the Katsuura Bay. As the results the shape of shore reefs, the state of floating sand, the depth of the sea etc. are represented by equidensitographs using the texture. The interval of density slices is $\Delta D=0.05$. The digital graphs are analyzed by a hybrid system which consists of NOVA 02/30, a disk, MT (800 bpi, 9 tracks) etc. Correlations between the textures represented by equidensitographs, digital graphs and analog display are estimated.

1. INTRODUCTION

Coastal phenomena have many different characteristics from coast to coast¹. In this report the image processing of aerial photographs has been done to know various coastal phenomena such as characteristics of shore reefs and floating sand, the depth of the sea, and the status of sea pollution along the Kujukuri and Kashimanada Coasts and the Katsuura Bay on the Pacific coast of the Japan Islands.

The photographs were taken from the aircraft loaded with a multispectral scanner (MSS) and a multispectral camera (MSC). The location of the surveyed area is shown in Fig. 1 which was obtained from LANDSAT I. This area has been selected because it is characterized by peculiar beaches, floating sand and shore reefs, and marked pollution of rivers and also because the sea truth and ground truth are quite feasible there. Photographic processing and analog and digital processings after the information is collected by sensors and recorded in photographs with different bands are the purpose of this study.

As a Daedalus's MSS is used, the analog record is converted to photographic image by Honey's CRT and printer and then the photographic processing is given. Four Hasselblad's cameras are used as MSC to obtain different 4-band information. Spot measurement is made by a Bronica's beam split camera² designed by us.

Information of infrared and three bands of visible region is obtained by the beam split camera and these 4-band photographic images are given the photographic, analog and digital processings.

As photographic processing, the 3-band separation method by means of reproducing dyes in the image by use of a thin layer chromatograph (TLC)^{3,4}, an equi-density reproduction ($\Delta D=0.05$) by the density slice method, and a method of reproducing the image in an half-tone equidensitograph by use of a contact screen (133 lines/inch) are examined.

As analog processing, there are an electro-image processing by use of a multicolor system (4200) with a three-channel videocon camera and a photographic image processing by use of Canon's multispectral viewer (MSV-300).

As digital processing, the system is used which was designed by us and assembled by Shimadzu Seisakusho Ltd., and named CIC-10. This hybrid system consisting of NOVA 02/30 (32 kW), a disk (2.4 MW), MT (800 bpi, 1600 bpi) etc. has a function of color displaying. As input device a plane scanner and a videocon camera are used. The signals from the input device are converted to A/D and transmitted to CPU through an interface. Besides the information is processed by the use of the MT to Varian 72 and a color image recorder, Dycomed (D-47). CIC-10 system is shown in Fig. 2.

After finding the correlation between the textures reproduced by the photographic image, analog image, digital image obtained by the image processing by use of these devices and further by ground truth, these images are discriminated and estimated.

2. EXPERIMENT

Our study is a part of the comprehensive research by the National Institute of Resources of the Science and Technology Agency and deals specifically with image processing. It also includes the remote sensing surveys of Kasumigaura Lake as specific study of the Ministry of Education and the image analysis of photographic images or magnetic tapes with the information of the world known whirls in Naruto with regard to the bridgebuilding between the main land and Shikoku by the Ministry of Construction of Japan.

In this report the various coastal phenomena are estimated by the processing and analysis of images obtained by aerial sensing along the Kujukuri Coast, Kashimanada Coast and Katsuura Bay in Chiba on the Pacific coast of Japan.

2.1. AERIAL SENSING

The airplanes used in this study were bimotored, and sensors were a Daedalus's MSS, a multiband camera with four Hasselblad's cameras, and a beam split camera designed by us and made by Bronica Co. We reported previously² on a handy field-averaging spectrograph camera in the field of remote sensing application and proposed the combined use of the field-averaging spectrograph camera and the beam split camera. Though the beam splitter of the camera is changeable according to the difference of sensitivity of the films, in practice the rays reflected by the beam splitter, which has 20% reflectance, reach a film (Kodak aero-color negative 2445) through a filter (HF-3). On the other hand, the rays which have transmitted the splitter reach a different film (Kodak infrared aerographic film 2424) through a filter (Wratten 88A), while the exposure is compensated by N.D. filters.

2.2. REMOTE SENSED AREA

The aerial sensing of the Kujukuri Coast and Kashimanada Coast was carried out on April 18, 1974. The flight height was 2500 m and twelve points in the sensing area were sensed using a Daedalus's MSS and a spot camera as sensor. The spectral distribution from the sandy beach of the Iio Coast in Chiba was measured by use of a radio spectral meter and the results are shown in Fig. 3, in which the spectral distributions of the dry portion and the waterside are different remarkably. The absorption ratio of the sea water in regard to the depth is obtained from the measurement of the spectral distribution of reference white boards submerged in the sea. The photograph measured by an MSS is shown

in Fig. 4. Though the conditions of the sea are classified by false colors, only reproduction pattern is shown in Fig. 5.

The spot photograph on an aerocolor negative film of the mouth of the Tone River near the Kashimanada Coast presents distinct information. The colored dyes of the sensitive layers of the film in the bands at 450, 550, and 650 nm are reproduced completely by the TLC method. These three layers are separable in the image on a B/W film by this method. One of the merits of the TLC is that it exerts a good resolving power of the image not only because the tricolor separation filter can be used, but also because the interlayer color mixture is avoided effectively. From analysis of the contents of the colored dyes of color negative its absorbance is recognized and the separation exposure is determined. As the textures obtained by this method are separated into three prints and if one band of infrared image is added, it would be more effective in the remote sensing processing. Then a beam split multiband camera is made as trial. The status of pollution of rivers are well recognized from the textures obtained by this camera.

The aerial sensing of the Katsuura Bay in the southwest of the Kujukuri Coast was done from the height of 1500 m by use of a multiband camera with four Hasselblad's cameras and an ITV camera with 60% overlap on November 28, 1974. At the same time the sea truth was done and the reference white boards in the sea was recorded on the film. From the textures obtained the various coastal phenomena such as the characteristics of shore reefs and floating sand are analyzed by the density slice method and digital method. The results obtained by the density slice method and digital method are shown in Figs. 6(a) and 6(b), respectively.

3. IMAGE PROCESSING AND ITS ANALYSIS

There are a density slice method and a contact screen method for the photographic image processing⁵. In the image processing of color films a photographic image is separated into different B/W images by respective colors. The density slice method is shown in Fig. 7. An equidensitograph is obtained by giving the exposure so that the required density range exists in the valley of the characteristic curves of a high contrast film. As the accuracy of the interval of equidensito-slices is $D=0.05$, this method is of great utility. As the visual interpretation of the information is easy by comparing the confirmed measurement point and the equidensitograph in this method, it will be useful as an analog picture. As this method is useful for the enhancement of the reproduction point, a device with which a slice matrix will be composed automatically is required. In the processing using a contact screen a contact screen of 133 lines/inch was used. This method is regarded as a digital method by photographic paper. In the processing, as the required density point is reproduced by use of matrix screens of different density levels, the percentage of dots in the screen is selected for reproduction.

In the analog processing, the reproduction of the density, the conversion of phases, the switching of channels etc. are possible in a short time. Therefore it is convenient for quick reproduction of images, but the image accuracy in this method is lower than that in the photographic image processing method. As the output of the analog signals is much less stable, the analog processing is considered as an instantaneous enhancement of the image. On the other hand the image from a multi viewer having a function of multiplexing of three color beams is stable because the texture is the photographically processed image. However, as the conversion of phases and the equidensitograph of the image depend on the photographic processing, an analog image represented by an optical system is considered as a part of the photographic processing.

In the hybrid system shown in Fig. 2, the RDOS's software and the BICOM's software are used for the digital processing and analog processing, respectively. The merit of this system is an off line transfer to the system with Varian 72 and a film recorder Dycomed 47 which may be localized in a different place. The system of Varian 72 is connected with our system by off line by use of MT (800 bpi, 9 tracks).

Thus our system embraces every technical field of a photographic processing.

an analog processing, a digital processing and a separation method and so it is ready to construct many softwares for the pattern recognition based on the ground truth, keeping the correlations between these fields.

4. STUDIES IN PROGRESS

A remote sensing simulator has been designed for the measurement of soil moisture and scenic factors. The simulator is a device with a polarimeter as shown in Fig. 8. The soil moisture of the Shirako Beach on the Kujukuri Coast measured by this simulator is shown in Fig. 9.

In the measurement of pollution by the sand brought for construction on the coast, the relation between the sea depth and suspending substances should be made clear. Therefore the above simulator will be used for this purpose also. Breaking waves may be a noise in aerial sensing of coastal pollution, and so the removal of such a noise from remote sensing images including the information of reflection on the sea surface is a problem to be solved in the future. The computer calculation of the information obtained by a field-averaging spectrograph camera and the figure reproduction of spectral reflection and transmission by a hybrid calculation are also future problems.

5. CONCLUSION

A great deal of experimental data must be accumulated to carry out fundamental studies and to put theories into practice. By these photographic and digital processings of image information obtained mainly from coastal area, the area of floating sand and sea pollution has been confirmed and the location of shore reefs has been recognized. In the remote sensing measurement all information is made clearer by the comparison with reference objects.

In the photographic processing of various coastal phenomena, it is considered to be extremely significant to separate an image into three bands by use of color films.

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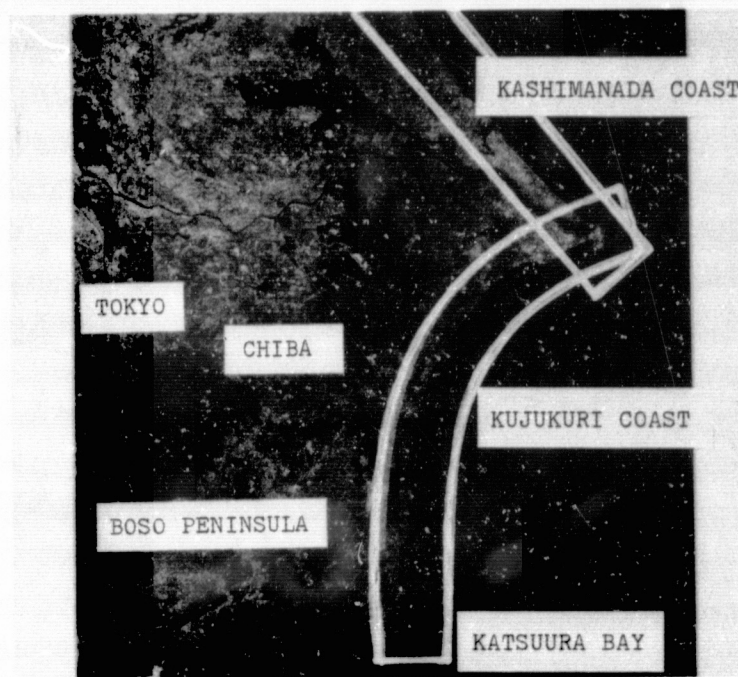


FIG. 1. LOCATION OF THE SURVEYED AREA.

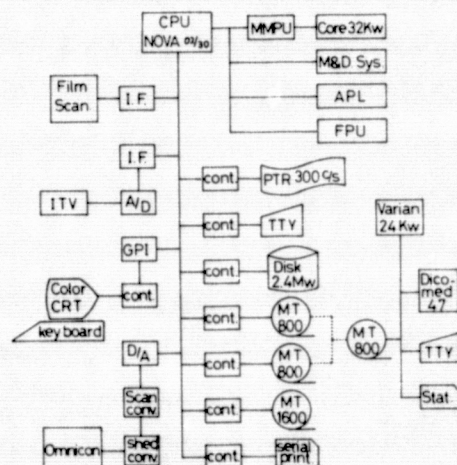


FIG. 2. HYBRID SYSTEM (CIC-10) FOR IMAGE PROCESSING.

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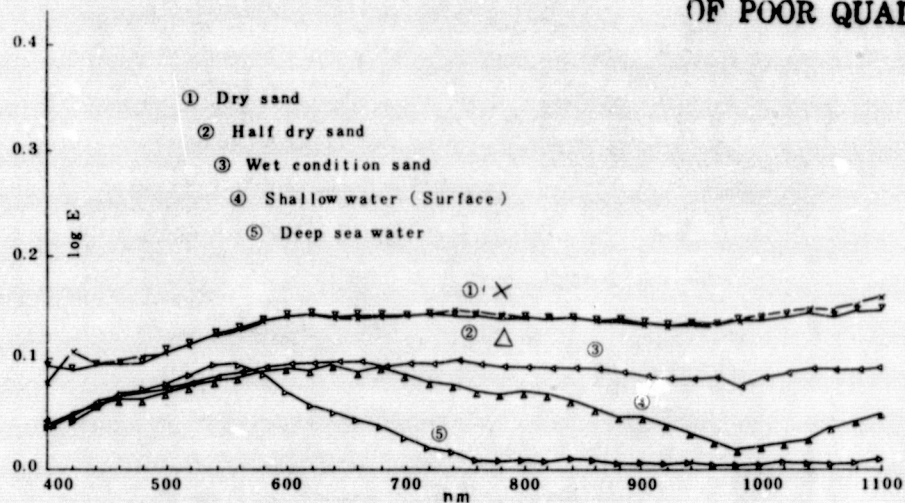


FIG. 3. CHARACTERISTICS OF SPECTRAL REFLECTANCE. Sand and sea water on the Iioka Coast.



FIG. 4. PHOTOGRAPH BY AN MSS. Kujukuri Coast.



FIG. 5. REPRODUCED EQUIDENSITOGRAPH. Kujukuri Coast.

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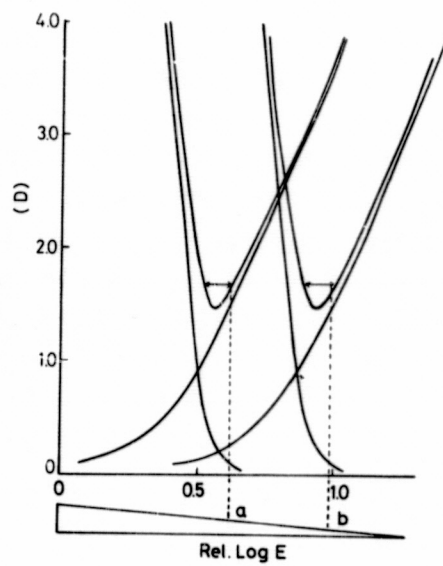


FIG. 7. REPRODUCTION CURVES OF EQUIDENSITIES.

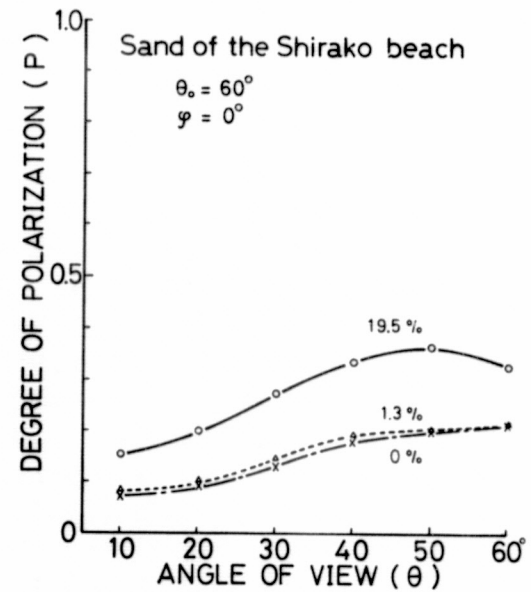


FIG. 9. SOIL MOISTURE. Sand on the Shirako Beach on the Kujukuri Coast.

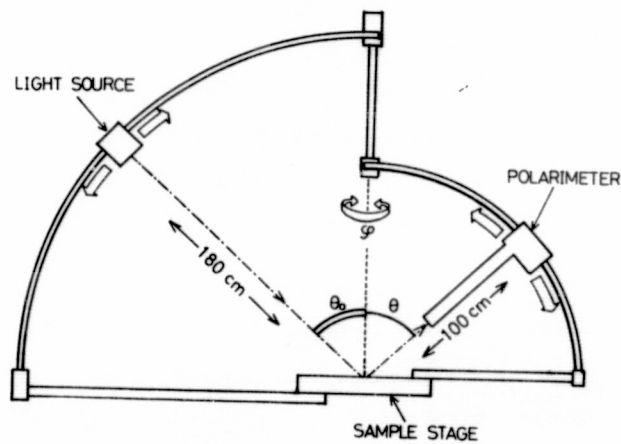


FIG. 8. REMOTE SENSING SIMULATOR.

N78-14507

LANDSAT DETECTION OF HYDROTHERMAL ALTERATION
IN THE NOGAL CANYON CAULDRON, NEW MEXICO

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SUMMARY

In 1974 a circular-shaped iron oxide anomaly was observed in an R54 ratio image of a LANDSAT frame centered near Truth or Consequences, New Mexico. Because the frame was processed for uranium exploration in the Rio Grande Valley this anomaly, located in Tertiary-aged volcanics, was not immediately field checked. A recent (1976) publication of Cenozoic volcanics in Southwestern New Mexico containing a reconnaissance geologic map of the Nogal Canyon Cauldron rekindled interest in the observed ratio image feature, which covers approximately 2% of the area in the cauldron. The cauldron itself is roughly circular in shape, with an approximate 16km diameter. Field examination of an R54 anomaly just southwest of the circular anomaly, but still inside the cauldron, has shown that it coincides with a zone of hydrothermal alteration on the northern edge of the Nogal Canyon Cauldron. The altered area contains clay minerals ranging in colors from white to vivid red, the latter presumably resulting from hematite staining. In situ gas measurements showed no evidence of active hydrogen sulfide seepage. Preliminary geochemical analyses of grab samples have detected no significant amounts of mineralization. Whereas this area does not at present appear to be economically important, it provides an example of how LANDSAT can be utilized in reconnaissance mapping for cauldrons, calderas, and other volcanic features which display hydrothermal alteration. Extraction of four-channel LANDSAT spectral signatures from the anomalous region and from ferric oxide-rich sediments in the Rio Grande Valley showed that on a purely spectral basis, secondary iron oxides of the altered area could not be uniquely discriminated from unimportant primary ferric oxides of some of the sediments, except for bright altered areas on sunward slopes, where topographic differences made the single channel values higher for the altered areas than the more flat-lying sediments. However, the circular shape of the anomaly and its location in Cenozoic volcanics, in addition to the localized occurrence of ferric oxides, makes this feature unique in the whole LANDSAT frame. It is important that spectral and spatial information be used together for mineral exploration with satellite data. Geometrically accurate transparencies of whole-frame ratio images and automatic recognition maps overlaid onto geologic maps of the same scale are well suited to this task.

INTRODUCTION

In 1974, an R54 ratio image (channel 5 divided by channel 4, after correction for atmospheric path radiance) of a LANDSAT frame centered near Truth or Consequences, New Mexico was produced by GeoSpectra Corporation for uranium exploration in the Rio Grande Valley. During that time, a circular area in young volcanics, unimportant for uranium but possibly important for copper, was discovered which had high R54 ratio values, indicating the presence of exposed ferric oxides. The shape and location of the R54 anomaly led to the hypothesis that this R54 anomaly could be an expression of hydrothermal alteration zones associated with a collapsed volcanic feature. By mutual agreement between GeoSpectra and Earth Sciences, Inc., G. Rouse field checked the area in the

summer of 1976. The purposes of this paper are to report the results of that field trip and subsequent LANDSAT data analysis of the anomalous area and to use this example to stress the importance of combining spatial and existing geologic information with spectral information in the application of satellite data to mineral exploration.

GEOLOGICAL SETTING

Figure 1 shows a black and white version of a portion of the New Mexico state geologic map. The area outlined in black corresponds to the approximate area covered by the R54 ratio image in Figure 2, which includes the Northwest quarter of the Truth or Consequences, New Mexico frame (ID 1334-17160), collected by LANDSAT I on June 23, 1973. Figures 1 and 2 are approximately the same scale. The small circular anomaly shown in Figure 2, about 2.4km in diameter, occurs in Tertiary-aged volcanic rocks about 65km south of Magdalena, New Mexico, in the San Mateo Mountains. This region is part of the Mogollon-Datil volcanic complex.

In a recent publication by W. E. Elston, et al. (1976), which came to our attention after interpretation of the anomaly in Figure 2, the Nogal Canyon Cauldron is described in reconnaissance maps as a roughly circular feature, approximately 16km in diameter, containing high-silica alkali rhyolite ash-flow tuff sheets and flow-banded rhyolites. They suggest that the high-silica alkali rhyolite arose from partial melting of the upper mantle and lower crust as a result of rising isotherms produced by the emplacement of basaltic andesite. According to their interpretation, the Mogollon Plateau is underlain by a granitic composite pluton some 125km in diameter. The Nogal Canyon Cauldron lies on the eastern extremity of this pluton.

Figure 3, taken from Elston, et al. (1976), shows the Nogal Canyon Cauldron as feature 1a. The 2.4km diameter circular R54 anomaly in Figure 2 is shown as a small circle just inside the northern rim of feature 1a in Figure 3. Allowing for the North arrow being left of vertical in Figure 2 and vertical in Figure 3, it is also possible to see what may be an outline of the Nogal Canyon Cauldron in the R54 ratio image of Figure 2, where the region inside the 16km diameter cauldron displays a slightly lighter tone than the immediately exterior regions.

FIELD DATA COLLECTION AND LARGE-SCALE SPECTRAL ANALYSIS

In the summer of 1976, G. Rouse made a field trip to the Nogal Canyon Cauldron area. Poor communications between authors led him to visit a smaller R54 anomaly southwest of the 16km diameter circular anomaly, but still within the cauldron. Figure 4 shows a large scale topographic map of the area shown in Figure 2 as a small rectangle around the circular R54 anomaly. The diagonally hatched area shows the regions that were observed to be hydrothermally altered. No field check was made in the circular anomaly itself, which would have required off-road transportation. The small square in Figure 4 encloses an area where a color ground-level photograph was taken (shown at the oral presentation of this paper, but excluded here). The o's denote where rock chip samples were collected for geochemical analysis, and the x's show the sample sites where sulfur gas readings were taken. The sulfur gas geochemical survey was conducted over the altered zone because previous work by Rouse and Stevens (1971) has shown that sulfur gas anomalies can be detected over sulfide deposits. More recent test work (unpublished) has shown that sulfur gas anomalies can be detected over some geothermal areas, also. Both sulfide mineralization and geothermal activity could reasonably be expected to be associated with a Tertiary cauldron located on the edge of the Rio Grande Rift. The gas survey traversed from unaltered volcanics on the southwest, across the southern edge of the altered zone, and over unaltered volcanics to the northwest and northeast.

Figure 5 shows a LANDSAT channel 7 graymap of the same area and scale as shown in Figure 4. Brighter areas in the channel 7 graymap are either sparsely

vegetated bright soils and rocks or dense green vegetation other than conifers, which usually are slightly darker than average in LANDSAT channel 7 relative to other terrain features, unless other green vegetative types underlie intermittently-spaced conifers.

Figure 6 shows an R54 ratio graymap of the same area and scale as Figures 4 and 5. The brightest areas in R54 should coincide with ferric oxide exposures. The redder the soil or rock, the higher is its R54 ratio, although green vegetation located within the same LANDSAT pixel (79 x 79 meters) as ferric oxides tends to reduce the R54 ratio for that pixel. In line 745, the pixel between columns 871 and 872 (this interstitial pixel is repeated once to preserve geometric accuracy with an IBM printer) and the pixel in column 872 corresponds to orange-red hydrothermally altered rhyolite in the color photo mentioned above. The 2.4km diameter circular anomaly shown in Figure 2 is shown in Figure 6 as the large bright area just north of center in the R54 graymap. The dark Southwest-trending linear feature cutting diagonally through the circular anomaly corresponds to a Northwest-facing slope (seen in Figure 4), which is probably more densely vegetated and partially shadowed at the time of the LANDSAT overpass.

Three high R54 slices were made to produce the one-ratio automatic recognition map shown in Figure 7. Unlike Figure 6, the darkest symbol was used for the highest ratio level in Figure 7. If vegetative cover is uniform, the highest levels of R54 correspond to the reddest soil and rock exposures. Hence, darker areas in Figure 7 should denote redder rocks and soils. The three levels of R54 mapped in Figure 7 are a subset within the highest R54 level (mapped as blanks) in Figure 6.

RESULTS AND CONCLUSIONS

The sulfur gas survey indicated that no anomalous sulfur gas was associated with the altered zone shown in the hatched area of Figure 4. Approximately 5 to 8 parts per billion sulfur (as SO₂) were found along the entire traverse, both in unaltered and altered terrain. Although only a small part of the cauldron was surveyed, it seems likely that the hydrothermal solutions which altered the volcanics in this portion of the Nogal Canyon Cauldron were not rich in sulfur gases.

The hydrothermal solutions did, however, extensively alter a large volume of Tertiary volcanic rock with end products of quartz, clay minerals, and iron oxides. Bleached zones and hematite stained zones were observed in the hatched area of Figure 4, as evidenced by the color photo (shown only in the oral presentation). It is likely that much of the 2.4km diameter circular anomaly, particularly those portions recognized in Figure 7, are also hydrothermally altered.

An analysis was made to determine whether the hydrothermally altered areas in Figures 4 and 7 could be spectrally separated from ferruginous bolson deposits in the eastern half of the Rio Grande Valley, but within the same LANDSAT frame. All four single channel and all six ratio values were extracted for approximately 20 pixels over each area. Whereas the six ratios could not distinguish between most of the pixels from the bolson deposit area and pixels from the hydrothermally altered area, a narrow range of values for single channels 4 and 6 were able to discriminate between the bolson area and approximately half of the pixels in the hydrothermally altered area. However, the alteration area pixels that could be spectrally discriminated from the bolson deposits were all located on sunward-facing slopes. Therefore, the greater brightness of these alteration zones, compared with the bolson deposits, was likely caused by topographic rather than chemical and textural differences between the two areas. Spectral ratios tend to suppress topographic differences, which help explain why the six ratios could not separate the two areas.

From this, it can be concluded that as far as the LANDSAT multispectral scanner is concerned, the hydrothermal alteration zones and bolson deposits are spectrally similar, excluding topographic differences. This implies either that the two materials are chemically and texturally similar or their differences are not detectable by LANDSAT. If the bolson deposits, which occur in a relatively high heat flow area along the Rio Grande rift zone, were reddened by hydrothermal activity or H₂S diffusion (for example, from underlying hot brines) along zones of weakness or unconformities, then the two areas could be truly similar, at least in ferric oxide content and degree of hydration.

Geochemical analysis of the rock chips collected at the locations shown in Figure 4 were performed. No sulfur was found in the samples and there were no anomalous values for copper, lead, zinc, silver, tin, tungsten, or titanium, as determined by emission spectroscopy.

This paper demonstrates that properly interpreted ratio images produced from LANDSAT data can lead geologists to hydrothermally altered zones in volcanic features which are considered to be favorable for metal deposits, particularly copper porphyries. Although LANDSAT cannot spectrally discriminate such areas from apparently less important oxidized areas in the same frame, the spatial configuration and physical location of the iron oxide anomaly can be used to reduce false alarms through sound geologic inference. The circular shape of the anomaly shown in Figure 2 and its location in Cenozoic volcanics, in addition to the localized occurrence of iron oxides, makes this feature unique in the entire LANDSAT frame. It is important that spectral and spatial information be used together for mineral exploration with satellite data. Geometrically accurate transparencies of whole-frame ratio images and automatic recognition maps overlaid onto geologic maps of the same scale are well suited to this task.

The fact that no economic mineralization was found in the area studies should not detract from the utility of the exploration method applied here. Had economic mineralization been found, this paper would not have been published.

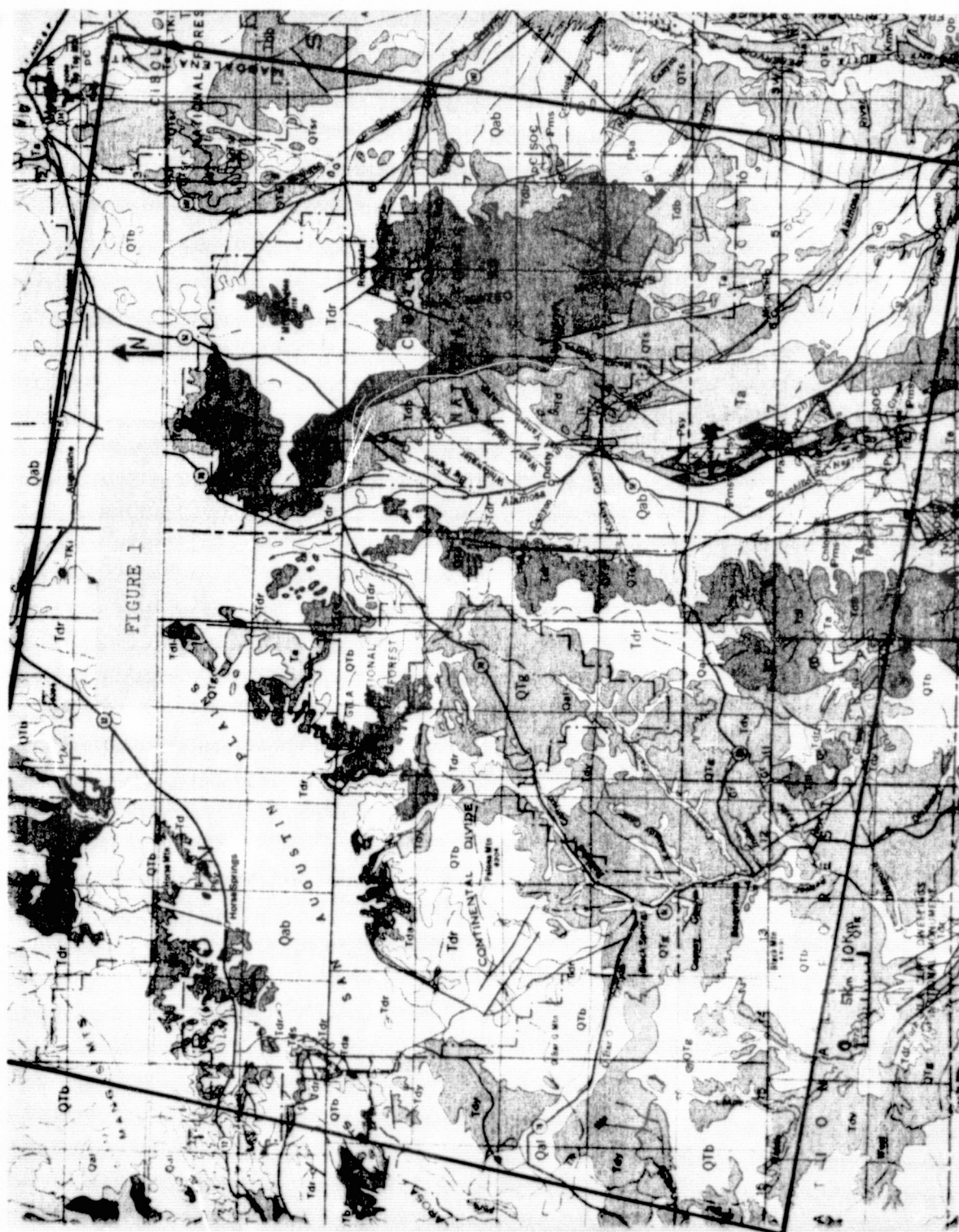
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FIGURE CAPTIONS

- Figure 1. State Geologic Map, Southwestern New Mexico. The area outlined in black is the region covered by the quarter-frame ratio image in Figure 2. The Tdl symbol refers to Tertiary-aged volcanics of the Mogollon-Datil Province.
- Figure 2. LANDSAT R54 Ratio Image. This quarter-frame area is the same scale as Figure 1, but the North arrow is skewed. Ferric oxides appear brighter than average. Note the 2.4km-diameter bright circular anomaly (within the rectangle) on the northern rim of a more subtle 16km diameter circular anomaly in the right-center portion of this image. The rectangle shows the area displayed in Figures 4, 5, 6, and 7.
- Figure 3. Map Showing Nogal Canyon Cauldron (After Elston, et al. 1976). The numbered areas show the known distribution of high-silica alkali rhyolite ash-flow tuff sheets. Feature 1a is the Nogal Canyon Cauldron, and the small circle on its northern rim is the 2.4km-diameter circular anomaly shown in Figure 2. Note that here North is toward the top of the figure.
- Figure 4. Large-Scale Topographic Map of the Nogal Canyon Area. The hatched area was observed in the field to be hydrothermally altered. Question marks signify regions that are likely altered, but were just beyond sight from the observed area. The small square shows the area covered by a ground-level color photo (shown only at the oral presentation), x's denote sulfur gas sample sites, and o's denote rock chip sample sites.
- Figure 5. LANDSAT Channel 7 Graymap of the Nogal Canyon Area. Bright areas in this graymap, which covers the same area at the same scale as Figure 4, are bright soils and rocks and dense, green vegetation other than conifers. The small square shows the area covered by a ground-level color photo.
- Figure 6. LANDSAT R54 Graymap of the Nogal Canyon Area. Bright areas in this graymap, which covers the same area at the same scale as Figure 4, are reddish ferric oxides. The small square shows the area covered by the ground-level color photo. The 2.4km diameter circular anomaly is the large bright feature just above the center of this graymap.
- Figure 7. LANDSAT R54 Density Slice of the Nogal Canyon Area. In this one-ratio automatic recognition map, which covers the same area at the same scale as Figure 4, the pound sign denotes $1.76 \leq R54 \leq 2.06$, the star denotes $1.68 \leq R54 \leq 1.75$, and the period denotes $1.64 \leq R54 \leq 1.67$. Though all three symbols indicate ferric oxide exposures, redder ferric oxides should have higher R54 ratio values. The small square shows the area covered by the ground-level color photo.

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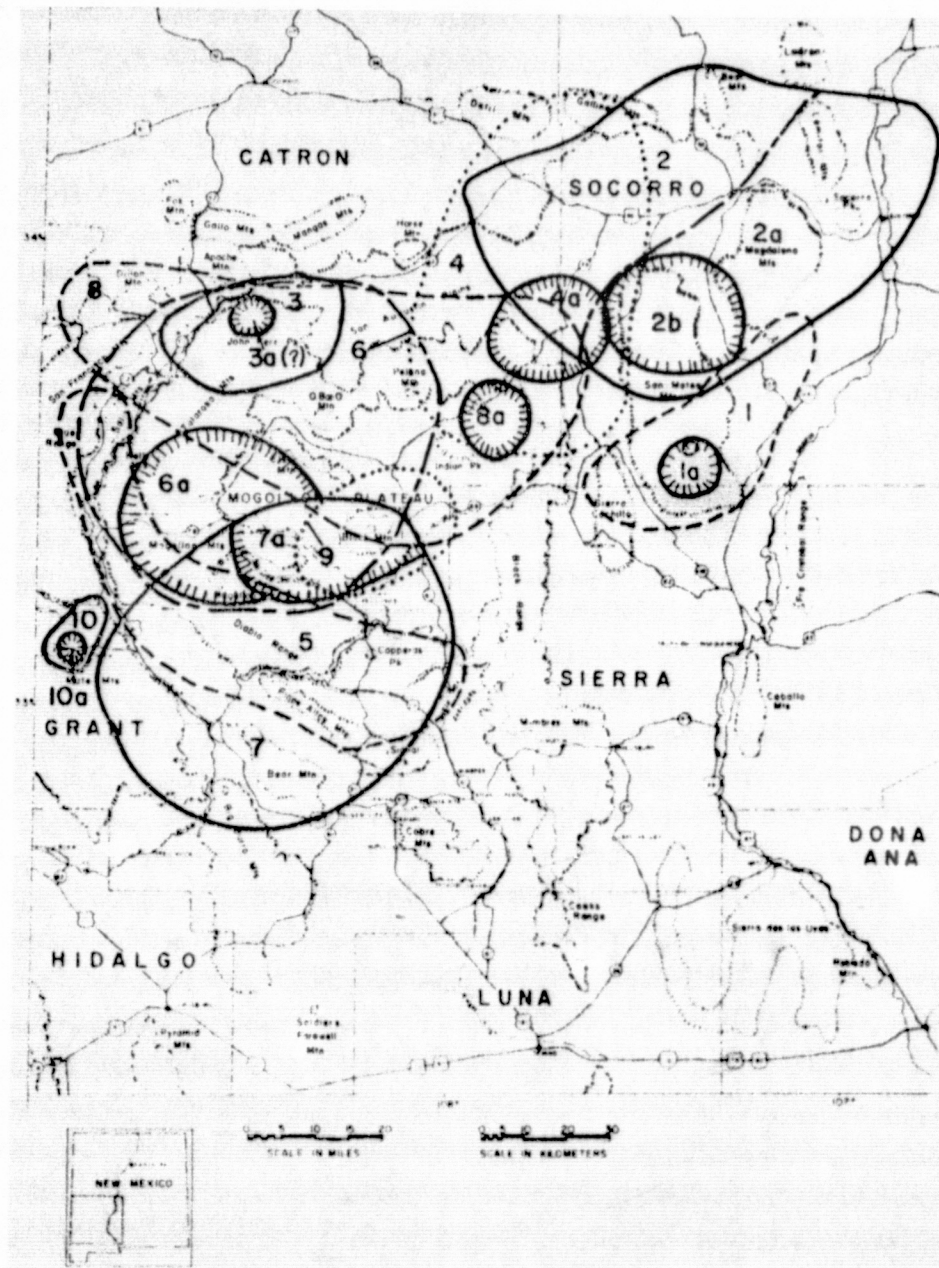
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FIGURE 2

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FIGURE 3



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FIGURE 4



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FIGURE 5

P	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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L	6	6	6	6	7	7	7	7	7	7	7	7	7	8	8	8	9	9	9	9	9	9	9	9	9	9	9	9
E	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1

FIGURE 6

P	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
L	1	8	8	6	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7
X	6	6	6	6	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7
L	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2

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AUTOMATED IMAGE PROCESSING OF LANDSAT II DIGITAL DATA
FOR WATERSHED RUNOFF PREDICTION

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ABSTRACT

The U.S. Soil Conservation Service (SCS) model for watershed runoff prediction uses soil and land cover information as its major drivers. Kern County Water Agency is implementing the SCS model to predict runoff for 10,400 km² of mountainous watershed in Kern County, California. The Remote Sensing Unit, University of California, Santa Barbara was commissioned by KCWA to conduct a 230 km² feasibility study in the Lake Isabella, California region to evaluate remote sensing methodologies which could be ultimately extrapolated to the entire 10,400 km² Kern County watershed. Digital results indicate that digital image processing of Landsat II data will provide usable land cover required by KCWA for input to the SCS runoff model.

INTRODUCTION

Preliminary remote sensing research has been conducted to demonstrate the feasibility of acquiring vegetation cover information for input to watershed runoff prediction procedures in Kern County, California (Figure 1). This work has been conducted in conjunction with the Kern County Water Agency (KCWA) which is charged with specific flood control responsibilities. Within their mandate, KCWA must develop storm runoff predictions for all watersheds in Kern County in order to:

- delineate flood plain boundaries which effect building standards for commercial and residential structures;
- establish building standards for specialized flood control facilities such as dams, debris basins, spreading ponds, etc., and
- provide base-line data for flood insurance.

Remote Sensing Unit personnel have been working with KCWA to demonstrate the feasibility of employing both Landsat digital data as well as aerial photography to generate land cover (primarily vegetation) information for input into the Agency's watershed runoff prediction procedures.

KCWA currently employs the runoff prediction procedure developed by the United States Department of Agriculture's Soil Conservation Service (SCS). In the SCS procedure, runoff Curve Numbers (CN) are based upon the soil-cover complex which are the major drivers of the runoff equation. Appendix A contains an example of the type and level of vegetation information required for the Southern California coastal plain and mountain regions to successfully operate

the model. The SCS runoff equation is:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}$$

Where: Q = runoff in inches
P = rainfall per storm
S = water storage factor equal to (1000/CN-10)
CN = a function of soil type, soil moisture, vegetation cover and density¹

At the present time, KCWA uses Table 1 data in order to determine field coefficients for input to the SCS runoff prediction equation. The current method of obtaining items 2, 3, and 4 in Table 1 of the soil-cover complex is by conventional field survey techniques. This method of data acquisition is both time consuming and expensive as KCWA is mandated to provide watershed runoff predictions for over 10,400 km² of mountainous watershed in Kern County. Since vegetation cover is a major driver of the SCS runoff model, the data generated by remote sensing will impact directly upon runoff curve numbers used by KCWA.

TEST SITE

The Lake Isabella test site (230 km²) for this preliminary investigation is in the north central portion of Kern County in the southern extension of the Sierra Nevada mountain range. Lake Isabella itself is at approximately 2000 feet above sea level at the confluence of the north and south forks of the Kern Rivers.

The test area possesses a number of distinctive woody plant communities common to Mediterranean climates. These communities include: evergreen stands, woodlands, evergreen scrubs (chaparral or hard chaparral), and drought-resistant scrubs (coastal sage or soft chaparral). Representative of the vegetation cover are: Chamise (*Adenostoma* spp.), mountain mahogany (*Cercocarpus betuloides*), Sumac (*Anacardinaeae* spp.), scrub oak (*Quercus dumosa*), mountain lilac (*Ceanothus* spp.) with several species of annual and perennial grasses and conifers present. Excepting deciduous *Quercus* spp. there are few deciduous trees in the study area.³ Chaparral occurs, in varying degree, at all elevations between 2000-4500 feet. The term chaparral generally describes an assemblage of shrubs, not a single specie. It should be noted that the chaparral of California is evergreen, winter active, and summer dormant, whereas the Rocky Mountain (*Petran*) chaparral is winter deciduous and summer active. The Mediterranean climate of the test area produces favorable growing conditions during the winter and spring months, followed by temperature and water stress during the hot, dry summer months. Annual/perennial grasslands and sage occur at lower elevations. Various types of woodland bisect chaparral brushfields in foothill areas (≈2000 feet) with riparian plant associations along canyon bottoms.

METHODOLOGY

Data Collection

A review of model parameters identified vegetation cover as being a major driver in the SCS watershed runoff procedure. Remote sensing methodologies for providing this data were investigated. Because of the large area (10,400 km²) that ultimately would require vegetation data, traditional air photo analysis presented several problems. First, photographic coverage of the study area was incomplete at a scale which would facilitate vegetation analysis. Second, initiating data collection flights to supplement existing aerial photography would have been too costly. Consequently, a digital image processing approach was implemented to solve this problem. A Landsat II computer compatible tape was obtained as the primary data set for the vegetation classification (see Figure 2). Collateral material consisted of vegetation maps generated by Kern County Water Agency's standard terrestrial windshield surveys, pan-chromatic aerial photography at 1:24,000 (Figure 3) and Kern County and USGS

geologic maps. In addition, larger scale photography was desired to supplement the 1:24,000 panchromatic aerial photography. Flight lines along Cook and Nichols peak regions using dual mounted 35 mm cameras yielded 1:5000 wide angle and 1:200 scale color aerial photography (Figure 4). The telephoto equipped camera recorded detail of the central portion of each 1:5000 frame.

Data Analysis

The Geography Remote Sensing Unit used a modified LARSYS computer software system for the analysis of the multivariate image data.³ The following text will deal with a description of the method used in the computer aided analysis (refer to Figure 5 flow diagram). The computer compatible tapes (CCT) were first preprocessed in order to reformat and correct system distortion. Analysis of the data began with clustering. Rather than clustering separate pixel regions throughout the study area, each containing a representative sample of all spectral classes, the entire feasibility study area was clustered (Figure 6). Unsupervised clustering identified the best combination of channels and the optimum number of cluster classes.⁴ Cluster analysis indicated whether cover types of interest could be identified solely on the basis of their spectral signature. Clustering also helped identify several confusion classes, especially those different classes with identical spectral signatures.

A zoom-transfer-scope was then used to superimpose the 1:24,000 panchromatic photography and the cluster map. Further analysis of the vegetation types was completed by comparing 1:24,000, 1:5,000 and 1:200 scale stereoscopic photography. As all vegetation classes of interest could not be identified solely by unsupervised clustering, supervised training class sites were selected throughout the study area. The algorithm used for supervised classification was the maximum likelihood discriminant rule based on a multivariate Gaussian assumption. Random selection of training sites was accomplished by selecting samples of the total population which represented each vegetation class of interest. Spectral statistics on 16 vegetation classes were originally determined and then each combination was tested using divergence/separability statistical analyses. The statistics process provided the mean and standard deviation vectors per Landsat channel, histogram by channel, and a coincident spectral plot for each vegetation class. The latter function provided a graphic representation by Landsat channel and grey level value for each vegetation class. Generally, those classes which were not represented graphically as spatially separate proved difficult to separate from each other when the maximum likelihood classification procedure was implemented. Those classes which display overlap in each Landsat channel were noted for further consideration. Furthermore, after evaluating the divergence/separability function, it was noted that certain classes and subclasses might be combined or excluded. For example, marginal sub-classes such as sand/barren were excluded from further consideration as the only available training sites were a few border pixels. Also the divergence analysis confirmed *a priori* assumptions that the sand/barren sub-class could not be separated from other classes of interest. Other classes such as Grass I and Grass II were combined as there was little difference in spectral response or the actual runoff numbers associated with each sub-class.

RESULTS

With training sites selected, test sites were randomly established throughout the study area to examine the effectiveness of a digital land cover classification. The classification map results are shown in Figure 7. Per pixel classification accuracies shown in Table 2 indicate that the computer aided analysis provides a viable method for vegetation cover data collection for input to the SCS method of watershed runoff estimation. Computer printout symbolization and nomenclature of vegetation for this portion of our study are currently being modified for greater compatibility with the user agency needs. For this study, the computer printout class Grass I consists of perennial grasses and weeds. The Brush/Grass class is dominated by soft chaparral and perennial grasses and weeds. The Pasture class is cultivated legumes. Woodland/Grass consists of an open cover of various species of oak, primarily scrub

oak and coniferous trees with intervening ground space occupied by perennial grasses and weeds. Brush I represents hard chaparral. The Mediterranean plant associations in Kern County, together with the level of vegetation identification required by the SCS method of watershed runoff estimation in this region, may have facilitated better results to be achieved than would be the case in other mountainous environments with greater population (vegetation cover) heterogeneity.

CONCLUSION

Both GRSU and KCWA personnel are encouraged by the high classification accuracy results achieved in this feasibility portion of the project (> 94% land cover classification accuracy). However, we are aware that increased resolution (both spatial and spectral) and improved software may be necessary to operationally achieve similar results in more complex mountainous environments, especially those non-Mediterranean plant associations with a greater number of conifer and deciduous trees.

Remote sensing methods employed in the Lake Isabella feasibility study area are currently being evaluated for accuracy and cost-effectiveness in order to extrapolate the computer aided methodology used here for land cover classification of 10,400 km² of mountainous watershed in Kern County, California

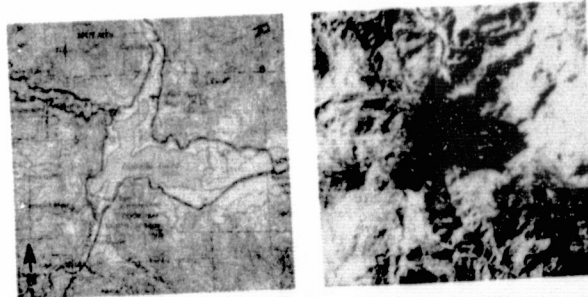
ACKNOWLEDGEMENTS

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LAKE ISABELLA WATERSHED
RUNOFF STUDY AREA
KERN COUNTY, CALIFORNIA



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Figure 1.

GREY MAP OF LANDSAT SCENE AUGUST 23,
1973 CHANNELS 4, 5, 6, AND 7

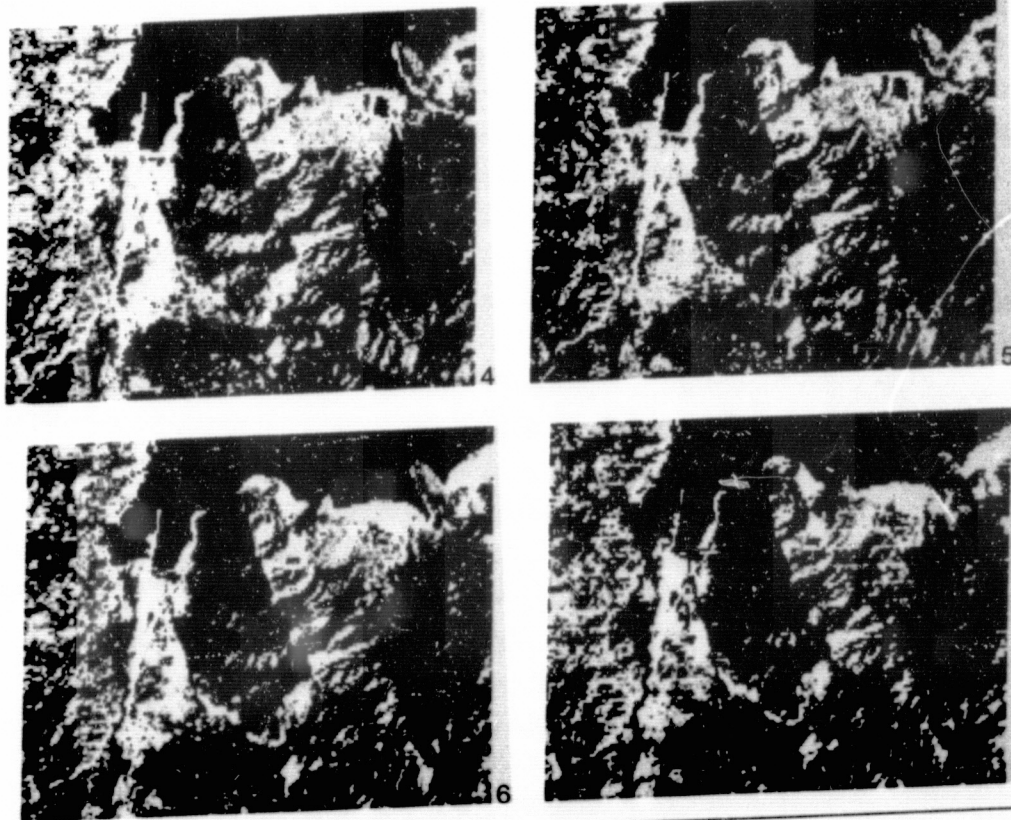


Figure 2.

PANCHROMATIC AERIAL PHOTOGRAPHY MOSAIC
OF THE NORTHERN PORTION OF THE WATERSHED
RUNOFF STUDY AREA 1:24,000



Figure 3.

MULTISTAGE STEREOSCOPIC COLOR AERIAL
PHOTOGRAPHY USED IN THE ASSESSMENT
OF WATERSHED VEGETATION 1:5,000 ; 1:200

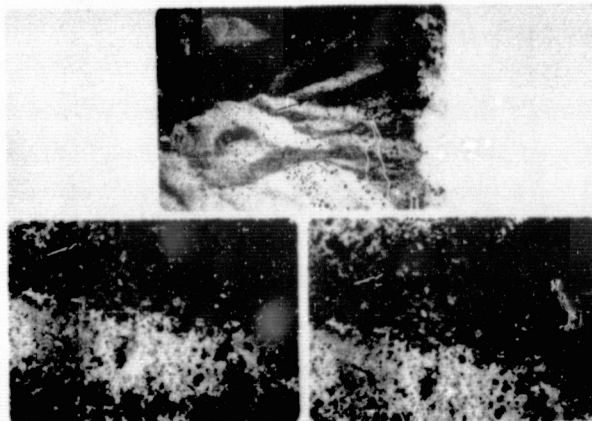


Figure 4.

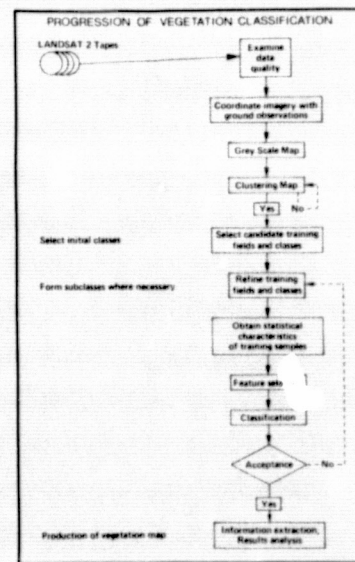


Figure 5.

CLUSTERING OF LANDSAT CHANNELS 5 AND 6
AUGUST 23, 1973 TO STRATIFY THE STUDY AREA



Figure 6.

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PER PIXEL VEGETATION CLASSIFICATION OF LAKE
ISABELLA WATERSHED RUNOFF STUDY AREA



Figure 7. Grass 1 (Ø) consists of perennial grasses and weed specie. Brush/grass (.) is dominated by soft chaparral and perennial grass and weeds. The pasture (:) is cultivated legumes. Woodland/Grass 2 (-) consists of an open cover of various specie of oak, primarily scrub oak and conifers with intervening space occupied by perennial grasses and weeds. Brush 1 (=) represents hard chaparral.

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TABLE I

EXAMPLE OF ARIZONA COUNTY WATER AGENCY
WATERSHED FACTOR EVALUATION*

WATERSHED: Ranch Canyon									
AREA: 24.3					AREA: 11.82				
Inches					Sq. mi.				
Evaluated By: _____									
(1) Sub Area	(2) Land Use	(3) Treat- ment or Practice	(4) Hydrologic Condition	(5) (6) Soil Texture Depth (inches)	(7) H. S. C.	(8) CN (9)	(9) Area (inches)	(10) Weighted CN Value X (8) 1/2 W Area	Remarks
A	Perennial Grass		Good	M 20-40	C	74	4.7	14.3	
B			Poor	C < 20	D	89	1.7	6.2	
C	Barren		Poor	C < 20	D	95	0.8	3.1	
D	Woodland Grass		Fair	C 10-40	C	76	8.3	25.3	
E	Woodland		Good	C 20-40	C	70			
F	Woodland Shrubland		Good	C 10-40	C	71/71	9.0	25.9	
								74.6	Total

1/ Poor is thin or sparse cover denoting less than 50% of the ground surface protected by
tiller, or by plant cover.
Fair is moderate or scattered cover denoting from 50% to 75% of the ground surface protected
by tiller or by plant cover.
Good is heavy or dense cover denoting more than 75% of the ground surface protected by
tiller or by plant cover.

2/ Hydrologic Soil Group

3/ Total Watershed Area (Inches)

4/ Coarse, medium, fine.

*Source: Kern County Water Agency Internal
Publication, 1976. This test watershed is
adjacent to the Lake Isabella study area.

TABLE II

TEST CLASS PERFORMANCE OF MAXIMUM LIKELIHOOD
CLASSIFICATION OF LANDSAT CHANNELS 4, 5, 6, and 7

GROUP	NO. OF SAMPS	PCT. CORRECT	NUMBER OF SAMPLES CLASSIFIED INTO					
			GRASS1	BRUSH/GR	PASTURE	WOOD/GR2	BRUSH1	WATER
1 GRASS1	19	94.7	18	1	0	0	0	0
2 BRUSH/GR	45	95.6	2	43	0	0	0	0
3 PASTURE	27	100.0	0	0	27	0	0	0
4 WOOD/GR2	48	81.3	0	4	0	39	5	0
5 BRUSH1	25	100.0	0	0	0	0	25	0
6 WATER	90	100.0	0	0	0	0	0	90
TOTAL	254	95.3	20	48	27	39	30	90

OVERALL PERFORMANCE (242/ 254) = 95.3

AVERAGE PERFORMANCE BY CLASS (571.5/ 6) = 95.3

APPENDIX A

Cover and Land Use for Hydrologic Soil-Cover Complexes of a Typical Watershed in Land Resource Areas 19 and 20, Southern California Coastal Plains and Southern California Mountains

For the purpose of classifying cover on a watershed in coastal and mountain areas of Southern California, the land uses shown in Chapter 9, Table 9.1 Section 4, Soil Conservation Service National Engineering Handbook, October 1971, are here modified to apply more closely to Southern California conditions. It is emphasized that the classification of land use into kinds of plant cover is intended entirely for estimating runoff.* Only those classes pertinent to the feasibility study area are listed.

Wildland

Areas with such natural or native plant cover as grass, brush, woodland-grass or woodland. It may or may not be used for grazing livestock. It includes abandoned cropland. Because the description of grassland, woods, and forest on page 8.3, Hydrologic Handbook, is too broad for application in Southern California, Wildland Land Use has been substituted and divided into the following kinds of plant cover.

Annual Grass - Areas on which the principal vegetation consists of annual grasses and weeds.

Broadleaf chaparral - Areas where the principal vegetation consists of evergreen shrubs with broad, hard, and stiff leaves. The brush cover is usually dense or moderately dense.

Meadow - Areas with seasonally high water tables, locally called cienegas, on which the principal vegetation consists of sod-forming grasses and other plants.

Narrowleaf chaparral - Areas where the principal vegetation consists of diffusely branched evergreen shrubs with fine needle-like leaves. The shrubs are widely spaced and low in growth. Where narrowleaf chaparral shrubs are dense and high, such areas will be included with Broadleaf chaparral ground cover.

Open brush - Areas on which the principal vegetation consists of soft-woody shrubs which are grayish in color. It also includes vegetation on desert-facing slopes where Broadleaf chaparral species predominate in an open shrub cover.

Perennial grass - Areas on which the principal vegetation consists of perennial grass, either native or introduced, and which grows under normal dryland conditions. It does not include irrigated and meadow grasses.

Woodland-grass - Areas with an open cover of broadleaf or coniferous trees and with the intervening ground space occupied by annual grasses or weeds. The trees may occur singly or in small clumps. Canopy density, the amount of ground surface shaded at high noon, is from twenty to fifty percent.

Woods (Woodlands) - Areas where coniferous or broadleaf trees predominate. The crown or canopy density is at least 50 percent. Open areas may have a cover of annual or perennial grasses or of brush. Herbaceous plant cover under the trees is usually sparse because of leaf or needle litter accumulation.

Barren - Areas with no, or practically no, plant cover; where 15 percent or less of the ground surface is protected by plants or litter. This includes rocklands, land destroyed by erosion, and shaped or graded land.

* Supplement to Chapter 9, Section 4 of the Soil Conservation Service National Engineering Handbook, October 1974.

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MICROWAVE MULTISPECTRAL INVESTIGATIONS OF SNOW

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ABSTRACT

A long-term observational program on the microwave emission and scatter behavior under controlled conditions has been started at a high-altitude alpine test site. All stages of development of the snow-cover during the whole season are under investigation. The purpose of this study is to achieve the required knowledge on the microwave radiative properties of snow for the optimization of the microwave payloads of air- and space-borne snow sensors and for the interpretation of large-scale snow maps obtained by these sensors.

Preliminary results of the first month of our investigation obtained with the radiometers at 4.9, 10.5, 21 and 36 GHz are presented.

1. INTRODUCTION

The usefulness of the microwave spectrum for large-scale mapping of the snow-cover has clearly been demonstrated, e.g., by utilizing the data of two channels of the Nimbus-5 Microwave Spectrometer (Künzi et al. 1976). The particular advantages of microwave sensing of snow are

- the all-weather capability, which is important for any periodic observation of a surface feature determined by precipitation;
- the penetration depth, which can help to estimate the water content of a not too thick snow cover;
- the specific spectral behavior of snow at microwaves, which allows to distinguish between the various states of snow.

The latter two of these microwave properties are not yet sufficiently investigated to allow for a reliable quantitative determination of the water content of a snow cover and of the state (melting, frozen, etc.) of the upper layers. Therefore a long-term program has been established to study the microwave emission and scatter behavior of snow. All stages of the development of the snow cover during the whole season are to be investigated.

In the data evaluation and interpretation particular emphasis is put on the correlation of the microwave emission and scatter properties (spectrum, polarization, incidence) with the classical snow parameters as temperature, moisture,

density and layering. But also more advanced ways of characterizing snow, e.g., by the crystallographic properties and by the meteorological case history (freeze and melt cycles, accumulation, etc.) are in use. The physical properties of snow depend on a complex combination of parameters, each of them undergoes continuous variations over wide ranges within short time scales. The multi-parameters of snow can only be sensed remotely by a suitable multi-parameter method (wavelengths, polarizations, incidence angles).

2. TEST SITE AND INSTRUMENTATION

A special test field has been selected which belongs to the regularly observed test area of the Swiss Federal Institute of Snow and Avalanche Research (EISLF) of the Weissfluhjoch near Davos. The altitude (2550 m) secures the appearance of all types of alpine snow quality during a sufficiently long season (November until end of May). The EISLF makes also available scientific support much exceeding their regular observing program. A microwave instrumentation has been developed following previous experiences (see e.g. Hofer and Schanda, 1974) at various wavelengths. Five radiometers at frequencies of 4.9 GHz, 10.5 GHz, 21 GHz, 36 GHz and 94 GHz, and additionally a scatterometer at X-band has been constructed and combined in a common instrument cabin. This cabin is mounted on a 16-meter tower allowing for measurements at all polarization angles and at all incidence angles between nadir and zenith. All horn antennas for the different wave bands have a 3 db beamwidth of approximately 10 degrees. Therefore the radiation properties of almost identical footprints on the snow surface are measured simultaneously over the whole spectral range.

3. MEASUREMENTS

During the first period of measurements only the four radiometers at frequencies of 4.9 GHz, 10.5 GHz, 21 GHz and 36 GHz have been in operation. The depth of the snow cover at our site was about 2 meters. This means the remaining nadir distance between snow surface and horn antennas was about 14 meters which is by far sufficient for the plane wave condition.

During the first month of observation (March/April 77) at about 15 days, measurements of the microwave emission behavior have been performed. In the following results of the period around April 1st 77, and in particular of this specific day, are presented.

Figures 1 and 2 show the dependence of the radiation temperature on the look angle (measured in degrees off nadir) for the earlier mentioned frequencies, and for a morning measuring cycle and an afternoon cycle respectively. At each "cycle" the angular range between nadir (0°) and 65° off nadir was scanned three times for each of the two orthogonal polarizations. The time consumed for each cycle was typically between 1 and 2 hours including repetitive calibrations against built-in loads at controlled temperatures and against the sky. There are possibilities to shorten considerably the time for the measurements by the improvement of the electronic equipment for the registration which is being implemented now, but also if only one scan is taken for each polarization of each cycle. The necessity of shorter measuring cycles to be representative for a specific state of the snow cover is demonstrated by Figure 3. On 2 April, a particularly quick warming-up during the morning cycle took place due to the meteorological condition on this day. A strong melting phase set in at about 9.00 a.m. which changed the emissive behavior drastically during only one hour for all wavelengths (only two are shown in Fig.3 for the sake of clarity), while on the other days (e.g. 1 April) the measuring points are scattered randomly around the lines drawn in Figures 1 and 2, and no systematic deviations were observed for the three scans of each cycle. The spectral behavior of the measurements on 1 April (as an arbitrarily chosen example) is summarized in Figure 4. There is a complete reversal of the spectrum between the morning and the afternoon measuring cycles.

The particularly strong frequency dependence of the wet snow measured in horizontal polarization is an evidence for the content of liquid water. Finally in Figures 5 and 6 the brightness temperatures appearing for the nadir angle of 30° as they developed between 30 March and 3 April are presented. There was no measurement in the afternoon of 31 March, and there was a failure in the measurement of the horizontal polarization in the afternoon of 30 March. For the horizontal polarization on the morning of 2 April are taken the values of the second scan; this is arbitrary, and the first trace would give a better representation of the morning situation but would enhance the behavior more than appropriate for this less reliable cycle.

4. DISCUSSION

As far as conclusions may be drawn at all from these preliminary results, the following seems obvious: During the period of observation which represents a meteorological situation typically for spring, there occurred a warming-up on each day around noon which resulted in melting and formation of water droplets suspended between the snow crystals while in the evenings the freezing was setting in and restored the snow cover of each day to a typical morning state. This cyclically frozen and melted snow surface is reflected in the reversal of the spectral behavior of the microwave emission: Volume scattering by the ice crystals at all wavelengths causes a more black-body like behavior at the lower frequencies with the much deeper penetration while the shorter wavelengths are scattered more efficiently by each crystal and thus reflecting more efficiently the cold sky. In wet snow however the high permittivity of the liquid water causes a stronger reflection (lower brightness temperature) at the lower frequencies, particularly obvious in the horizontal polarization.

A more comprehensive study with more statistics of the microwave measurements including many different states of the snow cover and systematic correlation to the conventional snow parameters is in progress and will be published elsewhere.

5. REFERENCES

- Künzi, K.F., Fisher, A.D., Staelin, D.H., Waters, J.W., "Snow and Ice Surfaces Measured by the Nimbus-5 Microwave Spectrometer", *J. Geoph. Res.* 81, 4965 - 4980 (1976)
- Hofer, R., Schanda, E., "Emission Properties of Water Surfaces at 3-mm Wavelength", *Proc. URSI Specialist Meeting Microwave Scattering and Emission from the Earth*, 17 - 23, edit. E. Schanda, Bern, (1974)

6. FIGURES

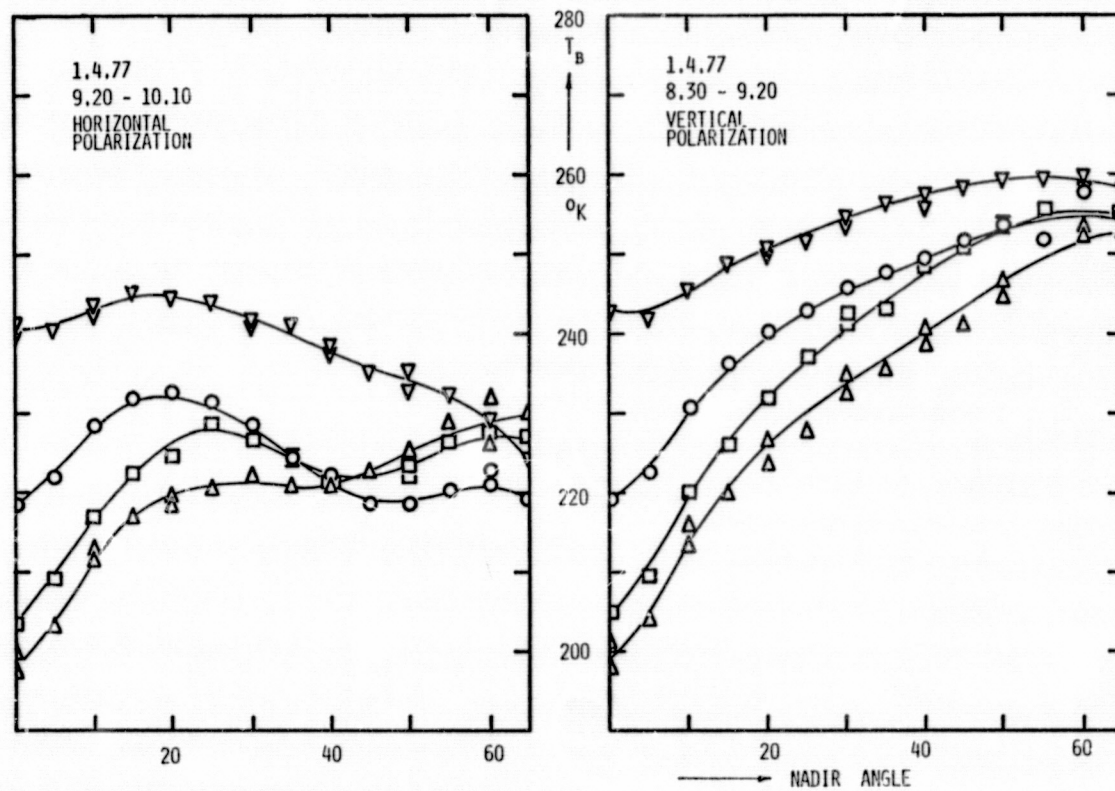


FIGURE 1. Dependence of the Brightness Temperature on the viewing angle (off nadir) for two polarizations at four wavelengths. Morning Measuring Cycle of 1 April 77.

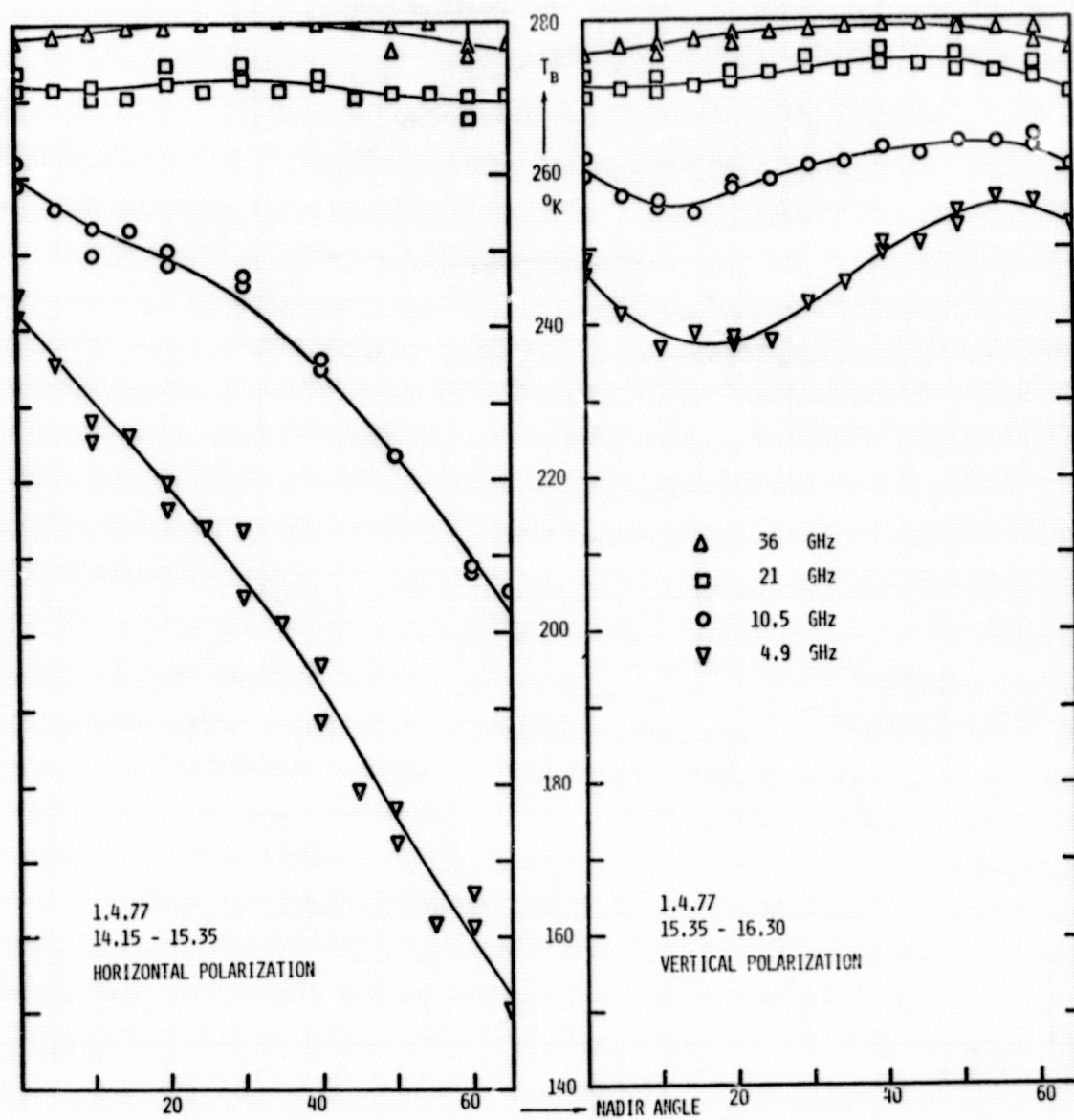


FIGURE 2. As Figure 1, Afternoon Measuring Cycle of the same day.

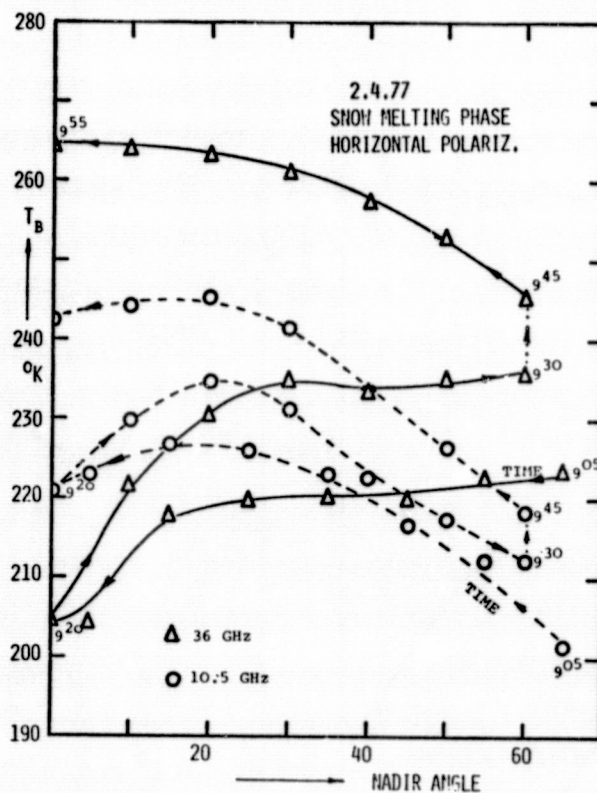


FIGURE 3. Effect of an extremely fast warming-up of the surrounding air on the scan of brightness temperature measured between 9.05 and 9.55 a.m.

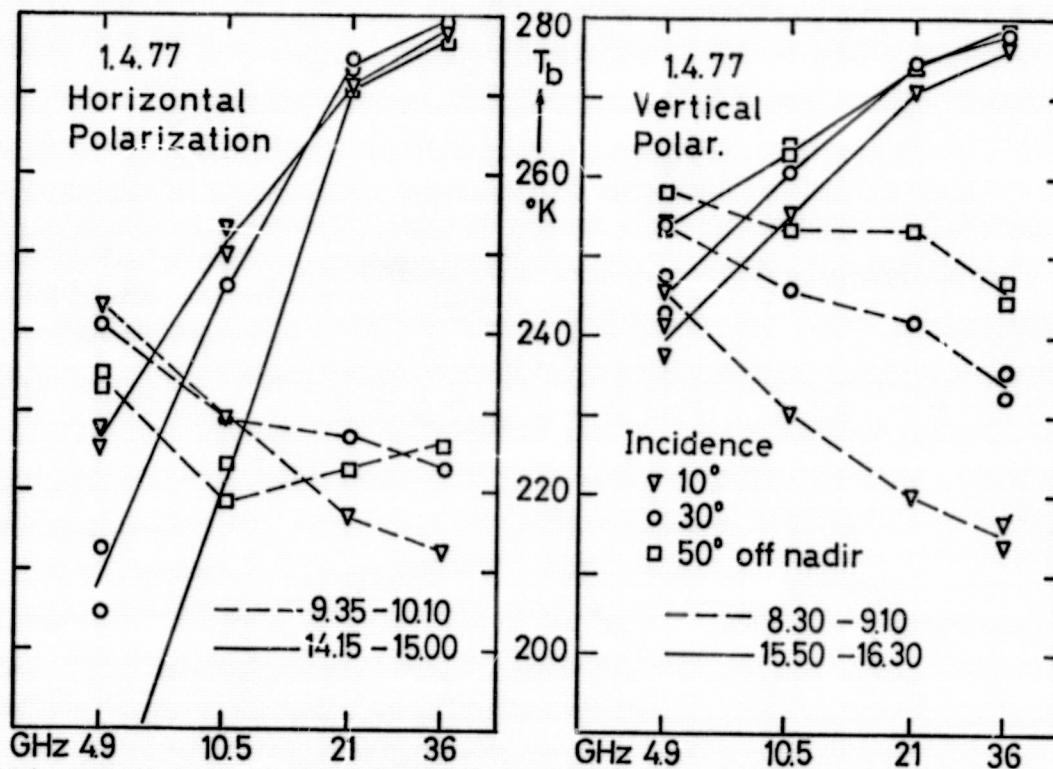


FIGURE 4. Spectral behavior of the brightness temperature of the morning and the afternoon measuring cycles of a specific day.

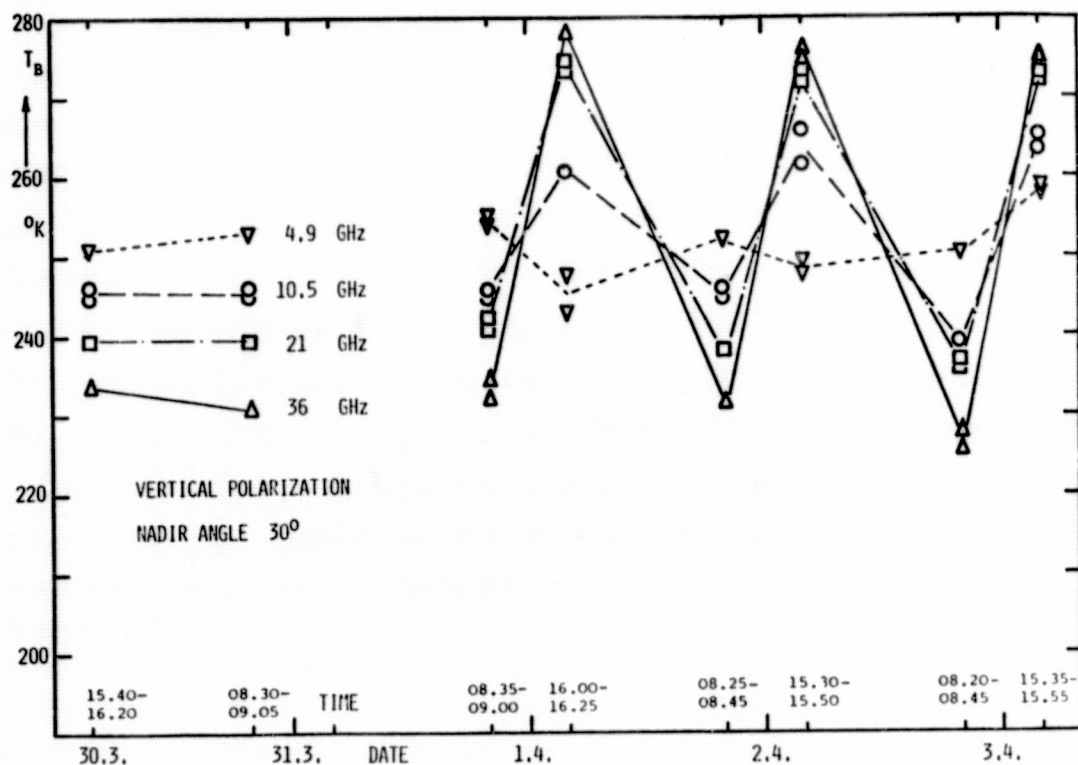


FIGURE 5. Brightness Temperatures at 30 degrees off nadir and vertical polarization of all measurements cycles performed between 30 March and 3 April 77.

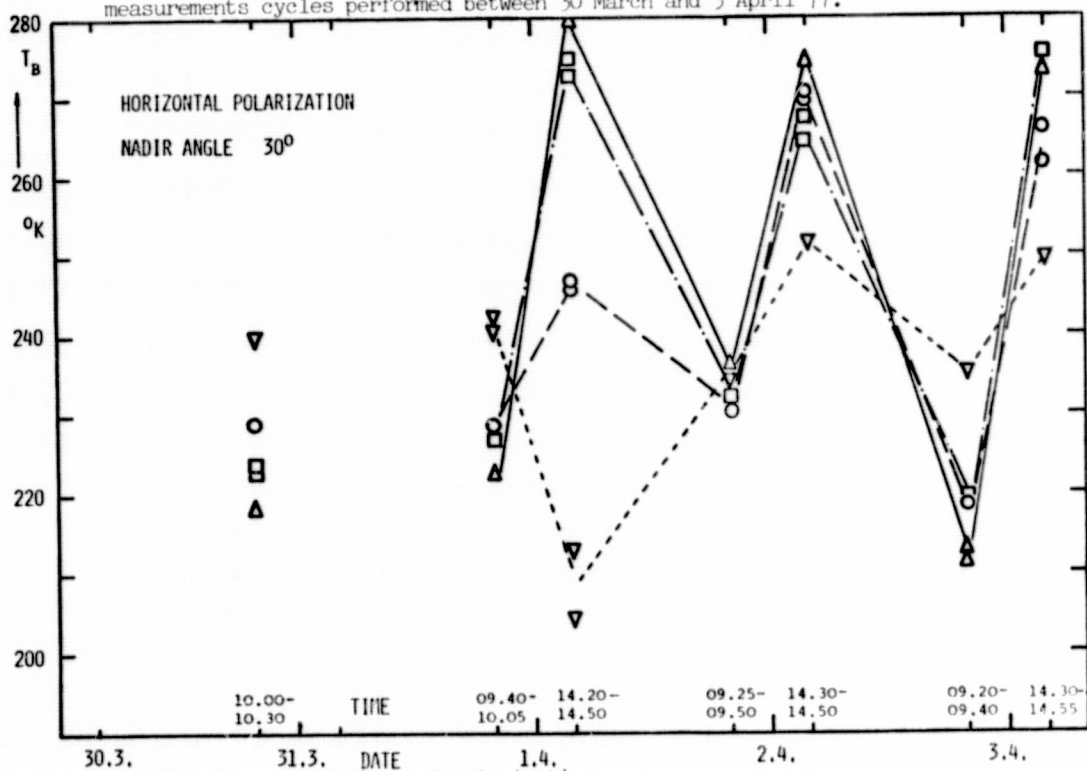


FIGURE 6. As Figure 5, for horizontal polarization.

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APPLICATION OF LANDSAT DATA
TO WETLAND STUDY AND LAND USE CLASSIFICATION
IN WEST TENNESSEE

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ABSTRACT

The Obion-Forked Deer River Basin in northwest Tennessee is confronted with several acute land use problems which result in excessive erosion, sedimentation, pollution, and hydrologic runoff. In order to assist with resource planning in this basin, the objective of this study was to demonstrate the application and utilization of Landsat data for determining land use of selected watershed areas within the basin, with special emphasis on determining wetland boundaries. Densitometric analysis was performed to allow numerical classification of objects observed in the imagery on the basis of measurements of optical densities. Multi-spectral analysis of the Landsat imagery provided the capability of altering the color of the image presentation in order to enhance desired relationships. Manual mapping and classification techniques were performed in order to indicate a level of accuracy of the Landsat data as compared with high and low altitude photography for land use classification.

The Remote Sensing Division at the University of Tennessee Space Institute (UTSI) made a study to provide the U. S. Soil Conservation Service (SCS) in Tennessee with needed resource information on the Obion-Forked Deer River Basin in northwest Tennessee. This basin is confronted with several acute land use problems which result in excessive erosion, sedimentation, and hydrologic runoff. The study was performed in conjunction with NASA to demonstrate the application and utilization of Landsat imagery for determining land use, especially for determining wetland boundaries. Within the river basin, the North Fork-Forked Deer River Watershed, an area of approximately 32,300 hectares, was selected for analysis.

Landsat imagery was obtained in the form of black and white transparency chips (1:3,369,000 scale) for all four wavelength bands. A 1:250,000 scale color composite was also obtained. Interpretation of the Landsat data was accomplished by use of a video-input analog/digital automatic analysis and classification facility at the UTSI Remote Sensing Laboratory. A light table

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was used to uniformly backlight each transparency and position them relative to a vidicon camera which converted optical density factors into electrical signals proportional to the amount of light received by the camera from each point on the image. An ISI VP-8 image analyzer accepted the video image input and was the primary tool for studying the imagery. The analyzer is capable of generating a horizontal and vertical cursor line pair onto a monitor screen with the intersection point of these movable cursors determining the image point whose output signal was digitized and read on a built-in digital meter.

The Landsat black and white chips were enlarged to 1:1,000,000 scale for analysis with this system. Further enlargement was attempted but the loss of resolution was too great. Since both bands 6 and 7 emphasize vegetation and the boundary between land and water, either is useful for distinguishing wetland boundaries. Band 6 was placed under the camera for analysis. By manually reading the analyzer digital meter and recording their values, 20 repetitions of relative light transmission measurements were taken on each of four types of scene elements: wetlands, urban areas, agricultural lands, and forests. A statistical analysis of the readings determined that a significant difference existed in the light transmission measurements of the four classifications except between urban and wetlands. Thus, these two classifications could not be separated.

By assuming a normal distribution of the data, the width of the classification ranges could be compared with the mean values plus or minus two standard deviations. This confidence limit of plus or minus two standard deviations of the data contained approximately 95% of the data points in each data set. The mean and standard deviation were calculated for each type of scene element so that the scene elements could be classified numerically with measured transmission values from 10 to 95 for urban, 22 to 69 for wetlands, 96 to 221 for forests, and 274 to 474 for agriculture. Since urban areas and wetlands showed the same signatures, these two categories could not be separated and thereby, the results of the statistical tests were supported. Figure 1 shows how these ranges appeared when shown as normal distribution curves.

The above data was contoured into areas of uniform image brightness with the results displayed on a television monitor modified to allow representation of the relative optical densities of the image in color coded form. When the output voltage corresponding to a point on the image being scanned was within the specified range as determined by the density readings, the color assigned to that voltage range was displayed on the monitor screen. Thus, the original black and white scene was reproduced with colors corresponding directly to the various brightness levels of the image.

Bands 4 and 5 were analyzed by the same densitometric methods. As shown in figures 2 and 3, the ranges overlapped to the extent that wetlands could not be separated from agriculture, and urban areas could not be separated from forests. However, these bands did show a significant difference in urban and wetland classifications which could not be separated on bands 6 or 7. Therefore, it seemed that a combination of band 6 or 7 with band 4 or 5 would permit the distinction of these two categories, and a multispectral additive color viewer was used to enhance both wetlands and urban areas.

Previous studies have shown that the primary criteria for the delineation of wetland patterns are the extremely dark red shades of bogs, marshes, etc.; the reduced infrared reflectance of plants growing in wet areas; and the black color of organic soils. Usually, these patterns are best seen using band 5 with no filter in combination with band 7 with a red filter. Several combinations of filters and light intensities were experimented with in order to enhance the target area. Except for the color composite, the band 5-7 combination did give better enhancement to wetland features than other combinations. However, the color composite using blue, green, red, and red filters respectively on bands 4, 5, 6, and 7 provided comparable enhancement of wetland patterns in addition to providing better enhancement of cities (blue or blue-gray color).

Manual mapping and classification techniques were used in order to indicate a level of accuracy of the Landsat data as compared with high and low altitude photography for land use classification. A map was prepared at two scales based on the Landsat color composite (1:250,000 scale). First, it was mapped at its

original scale so as to maintain the quality of resolution. Then, it was placed under a Bausch and Lomb Zoom Transfer Scope and enlarged to a scale of 1:130,000 in order to compare it to high altitude photography. At both scales of mapping, only Level I classifications were distinguishable: urban and built-up land, agricultural land, forestland, and wetlands. The North Fork-Forked Deer River appeared only as part of the wetlands since the vegetation is so dense along its banks. Due to the diversity in both kind and density of plant cover as well as surface moisture conditions, open or barren land and agricultural land both produce a wide range of color and total energy returns. Since these could not be separated, the agricultural classification also encompasses barren land.

High altitude photography (1:130,000 scale) of the North Fork Watershed was classified without enlargement. Level I classifications of urban, forests, wetlands, agriculture, and water could be distinguished. However, barren land could not be separated from agricultural land due to the fact that the photography was taken in November when most of the fields were bare.

Photo interpretation of 1:24,000 scale imagery was done, primarily, with the aid of a 5-power tube magnifier. Transparencies were viewed with mirror stereoscopes when certain objects required close scrutiny prior to their recognition. Photo interpretation was supplemented with information from 7½-minute USGS quad sheets. Separate map overlays were prepared for each quad in the effective area of the Watershed, showing land use classifications and wetlands vegetation. Final maps were prepared by photographing a base quad sheet in such a way as to obtain a subdued-tone negative and registering the base map negative containing the classification boundaries and annotations. The combined maps were printed for each quad at a scale of 1:36,000.

Areas were calculated for the various classifications at each scale by shading-in all similar classification categories on a map and employing density slicing techniques to measure the shaded portions. In comparing the various scales of imagery, the 1:24,000 scale photography was used as control data. The total area of the North Fork Watershed calculated at this scale was within 2% of the area as determined by boundary planimetry by SCS personnel. The percentage of difference or error was determined between the control data and each of the other scales (Table I).

For total area, the difference between the 1:130,000 high altitude and 1:24,000 scale imagery was determined to be only 8%. The difference between the 1:250,000 Landsat image enlarged to 1:130,000 scale and the control data was calculated to be 25% whereas the difference using the 1:250,000 Landsat image at its original scale was determined to be 20%. At each scale, the highest percentage of error was in the urban category. This would be expected because the resolution factors of small scale imagery limit the identification of isolated residential areas which are included in this category. Also, urban areas with an abundance of trees show spectral similarities to forests, and are therefore not easily distinguished.

The objective of this study was to demonstrate the application and utilization of Landsat data for determining land use of selected watershed areas in west Tennessee, concentrating on the determination of wetland boundaries. Using densitometric methods on each of Landsat bands 4, 5, and 6, it was determined that wetland boundaries could be easily separated from forest and agricultural lands on band 6. However, urban areas could not be distinguished from wetland areas with this method. Therefore, urban areas as well as wetland boundaries were enhanced by using a multispectral additive color viewer.

Mapping and classification techniques were used to determine the accuracy of Landsat and NASA high altitude imagery as compared to low altitude control data. Landsat can be used as well as high altitude photography for broad Level I classifications but with a lesser degree of accuracy. High altitude photography has comparable accuracy with low altitude imagery, but does not provide the additional detail of Level II classifications.

This study has shown that Landsat data can be used effectively to determine wetland boundaries. It can therefore be used to periodically measure remaining acreages and types of wetlands and to determine drainage trends, thereby providing needed resource information for management and preservation programs.

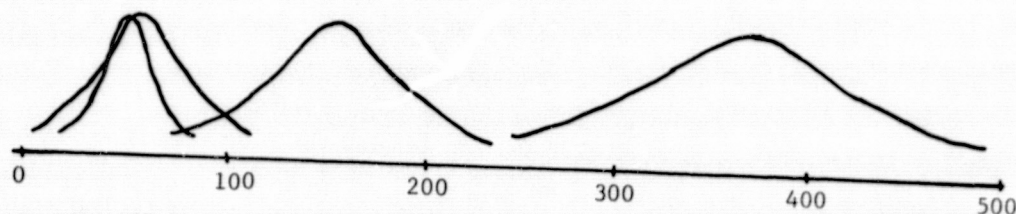


FIGURE 1. RANGES OF RELATIVE LIGHT TRANSMISSION MEASUREMENTS FOR FOUR SCENE ELEMENTS OF LANDSAT BAND 6 AS THEY APPEAR WHEN SHOWN AS NORMAL DISTRIBUTION CURVES.

URBAN 10-95 WETLANDS 22-69 FOREST 95-221 AGRICULTURE 274-474

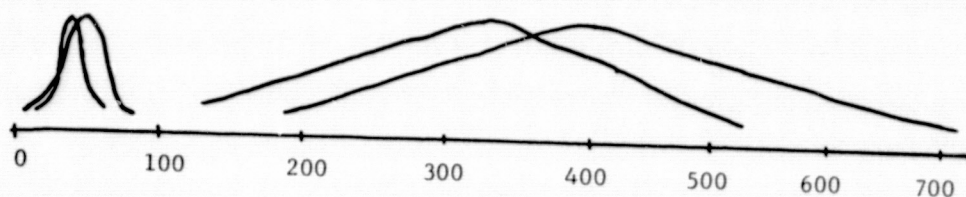


FIGURE 2. RANGES OF RELATIVE LIGHT TRANSMISSION MEASUREMENTS FOR FOUR SCENE ELEMENTS OF LANDSAT BAND 5 AS THEY APPEAR WHEN SHOWN AS NORMAL DISTRIBUTION CURVES.

AGRICULTURE 22-83 WETLANDS 26-49 FOREST 143-530 URBAN 196-703

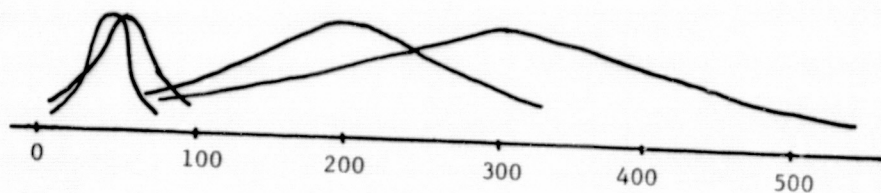


FIGURE 3. RANGES OF RELATIVE LIGHT TRANSMISSION MEASUREMENTS FOR FOUR SCENE ELEMENTS OF LANDSAT BAND 4 AS THEY APPEAR WHEN SHOWN AS NORMAL DISTRIBUTION CURVES.

AGRICULTURE 20-100 WETLANDS 23-63 FOREST 71-337 URBAN 82-549

TABLE I

AREA CALCULATIONS AND PERCENTAGE OF DIFFERENCE OF
HIGH ALTITUDE AND LANDSAT IMAGERY AS
COMPARED TO LOW ALTITUDE IMAGERY
(Area Expressed in Hectares)

SCALE	LOW ALTITUDE 1:24,000	HIGH ALTITUDE 1:130,000	LANDSAT 1:130,000	LANDSAT 1:250,000
<u>CLASSIFICATION</u>				
URBAN	1,961	873 55%	938 52%	481 78%
WETLANDS	2,100	2,465 17	2,865 36	2,570 22
FOREST	4,609	3,423 26	3,540 23	3,231 30
AGRICULTURE	23,454	27,860 19	32,770 40	32,239 37
TOTAL	32,124	34,621 8	40,113 25	38,581 20

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TESTING THE ACCURACY OF REMOTE SENSING LAND USE MAPS.

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A B S T R A C T .

In order to achieve wider acceptance among users of land use mapping from remote sensing data, the interpreter must be able to specify the accuracy of his product. Due to time and cost constraints, it would be virtually impossible, in the practical sense, to check completely each land use parcel throughout a region. Therefore, a valid sampling procedure is required to estimate classification accuracy. Stratified random techniques have been accepted as the most appropriate method of sampling in land use studies using remote sensing imagery, so that smaller areas can be satisfactorily represented. But the problem remains about how to select the best sample size for each category. Although several alternative methods have been used, none provide sufficient statistical justification for the allocation of sample points in each category of land use using remote sensing imagery. This paper describes a more detailed and more reliable method for determining the most appropriate (i.e., minimum) sample size.

The function of the ground truth survey in an operational remote sensing land use survey is to utilise a sound statistical sampling design which will test the correctness of the attribution by interpretation of specific sites to classes in the classification. That is, for any sample point, it should be shown whether the remote sensing attribution to a class within the classification is correct or in error.

Some of the main aspects that need to be considered in such a remote sensing sampling design are :-

- (i) the frequency that any one land use type (on the ground) is erroneously attributed to another class by the interpreter;
- (ii) the frequency that the wrong land use (as observed on the ground) is erroneously included in any one class by the remote sensing interpreter;
- (iii) the proportion of all land (as determined in the field) that is mistakenly attributed by the interpreter; and
- (iv) the determination of whether the mistakes are random (so that the overall proportions are approximately correct) or subject to a persistent bias.

This paper presents a sampling and statistical testing procedure which allows an approximate answer to each of these aspects. The concept developed and described in the paper, incorporates the probability of making incorrect interpretations at particular prescribed accuracy levels, for a certain number of errors, for a particular sample size. This contrasts with the usual practice of expressing the interpretation errors as a percentage of a subjectively derived number of sample sites. Consequently it is considered that this approach offers a more meaningful explanation of the interpretation accuracy level of an entire remote

sensing land use survey and also within each category.

The remote sensing sampling strategy presented in the paper has the added advantage that it can easily be adapted for use with most forms of remote sensing imagery, including orbital data. It provides a reliable framework for testing the accuracy of any remote sensing image interpretation - based land use classification using the minimum number of sample points; thereby saving time and money, especially if it is employed in operational surveys where high specification accuracy levels need to be guaranteed.

1. INTRODUCTION.

In recent years the development of techniques for collecting remotely sensed data has progressed very rapidly, but many problems still persist in the utilisation of the information. One of the main problems is the deficiency of appropriate techniques for establishing ground truth using satisfactory sampling techniques. (Kelly, 1970; Zonneveld, 1974; Allan, 1975). Therefore, in order to achieve wider acceptance among users of land use mapping, the interpreter must be able to specify the accuracy of his product. Due to time and cost constraints it would be virtually impossible, in the practical sense, to check completely each land use parcel throughout a region and so a valid sampling procedure is required to estimate classification accuracy.

2. SAMPLING PROCEDURE.

Financial and temporal limitations, combined with the problem of adequately representing important minor classifications in the areal sample, have tended to focus the attention of researchers involved in land use surveys towards some form of stratified sampling technique rather than a strictly random sample. The major difference between the two approaches is that with the stratified random sampling the areal sample space is divided into strata and each stratum is treated as a separate sub-universe in which random sampling is employed. (Kelly, 1970).

Most researchers have stated that they have adopted a particular strategy without fully describing the methods they used for selecting sample sizes, the location and areas of sample sites, and the criteria adopted for accepting or rejecting the sites.

Curtis and Hooper (1974) demonstrated that the notion of ground truth site varies according to the user's objective and the size of the study area. They suggested that the allocation of sample plots can then be estimated by 'the method of proportional allocation'.

Zonneveld (1972) strongly emphasised that random sampling in land evaluation surveys tends to give too much prominence to the larger areas to the detriment of smaller ones. He believes that the selection of points, within a fully homogeneous area as indicated by interpreted patterns on the imagery, should be random rather than using an overall random sample.

In an attempt to evaluate land classification procedures using simulated space photographs, Rudd (1971) considered that stratified random sampling was most appropriate. After interpretation, the area of each category was measured and the smallest was assigned five sample points and the other categories were allotted sample points in proportion to their respective areas. No reason was given for adopting five sample points for the smallest area. Doit and van der Zee (1974) discussed the importance of ground checks in the identification of rural land use by photo-interpretation in order to verify all non-identifiable and ambiguous objects as well as sampling each category to ensure the accuracy of the interpretation. No indication of sampling method or suggestions on appropriate number of sampling sites was given, but they did include some criteria for establishing interpretation accuracy, including the 85-95% limits suggested by Anderson (1971)

Stobbs (1968) used a random sampling method in order to measure land use in Malawi. He calculated the number of points to be sampled on each photograph by using a predetermined formula. Although it is one of the few published reports where the mathematical basis for determining the number of sample points is adequately detailed, the design parameters do not permit its extensive use. A similar sampling approach utilising the same formula was performed in Nigeria by Alford *et al.*, (1974).

Multi-stage sampling procedures have been used in studies associated with the production of land use maps from LANDSAT imagery. Usually, the interpretation of the land use patterns on the orbital imagery becomes the first stratification in the multi-stage design. This is then accompanied by several stages of sub-sampling using low and/or high altitude photography and/or ground data acquisition to quickly and efficiently check land use interpretations. Unfortunately, there are insufficient published details about this type of sampling design applied to visual interpretation techniques.

In summary, stratified random sampling techniques have been readily accepted as the most appropriate method of sampling in land use studies using remote sensor imagery, so that smaller areas can be satisfactorily represented. But, the problem still remains on the selection of best sample size for each category. Several alternative methods have been used, e.g.,

- (i) stratify the region geometrically and then randomly select points within each square or rectangle (Berry and Baker, 1968). The number of points may be determined by utilising formulae, (Stobbs, 1968; Alford *et al.*, 1974);
- (ii) stratify the region by interpreted land use categories, then estimate the total number of sample points that could be visited due to the constraints imposed by time and money, and subsequently distribute the them proportionally by area (Zonneveld, 1974);
- (iii) stratify the region by interpreted land use, allocate a certain number of sample points to the category with the smallest area, before distributing sample points to the other categories in proportion to their area (Rudd, 1974).

It is considered that the above methods do not provide sufficient statistical justification for the allocation of sample points in each category of rural land use utilising LANDSAT MSS imagery. Consequently a more detailed and more reliable method for determining the most appropriate (i.e., minimum) sample size should be ascertained. To meet this requirement the following procedure has been developed and successfully employed in operational projects. A fuller description of this methodology may be found in van Genderen and Lock (1976).

2:1 Sample Size

The function of the ground truth survey in an operational system is to utilise a sound statistical sampling design which will test the correctness of the attribution, by interpretation, of specific sites to classes in the classification. That is, for any sample point, it should be shown whether the remote sensing allocation to a class within the classification is correct or in error.

Some of the main aspects that need to be considered in such a remote sensing sampling design are:-

- (i) the frequency that any one land use type (on the ground)

is erroneously attributed to another class by the interpreter. For example in Table 1, 3/15 of A is erroneously attributed to other classes;

- (ii) the frequency that the wrong land use (as observed on the ground) is wrongly included in any one class by the remote sensing interpreter. For example in Table 1 5/17 of A allocations are wrongly interpreted;
- (iii) the proportion of all land (as determined in the field) that is mistakenly attributed by the interpreter. For example in Table 1 8/51 of all attributions are incorrect, and
- (iv) the determination of whether the mistakes are random (so that overall proportions are approximately correct) or subject to a persistent bias. For example, in Table 1 there may be a significant tendency to misattribute land use C (on the ground) to category A, i.e., 4/16.

Thus the successful design of a sampling and statistical testing procedure will allow an approximate answer to each of these aspects.

In order to determine the optimum size (defined as the minimum number of points that need to be checked in the field in order to meet a specified accuracy requirement) for a stratified random sample of a region which has been mapped by remote sensing techniques, it is necessary to consider, primarily, one land use type or category (stratum) which has been identified from remote sensing imagery. A sample of x points in that land use type can then be selected and the number of errors (f) checked in the field.

If such a procedure adopts a very small sample (e.g., $x = 10$) the number of errors would normally also be small (e.g., $f = 0, 1, 2$). However, the achievement of perfect results (i.e., $f = 0$) in such a small sample does not imply that the method is error free, as the result may occur by chance in a situation where a substantial proportion of the land use classification was in fact, erroneous. This fact is seldom appreciated by many image interpreters when checking the accuracy of the results of their remote sensing land use survey. The proportion of the interpretation which is in error would be identified in a very lengthy study, and is normally called $p\%$ (or p as a decimal fraction). The probability of making no interpretation errors when taking a sample of x from a remote sensing based classification, with real errors having a probability p , is given by the binomial expansion $(p+q)^x$ in which $q = 1 - p$. In the case of no errors in the interpretation, the last term of the expansion is the only one of interest (i.e., q^x).

Table 2 shows the probability of scoring no interpretation errors in samples of varying sizes taken from a population with a range of real error proportions q . This table indicates that no error sample results can quite easily arise in small samples when the true error rate is high. Taking the conventional probability level of .95/.05 (95% / 5%), the table can be divided into two parts by a 'stepped' line. Above and to the left of the line the probability of obtaining error free samples decreases, even though true errors may still be present in appreciable numbers, while below and to the right of the line, it is possible to identify the high probability that an error free sample could only have been obtained from a method that was relatively free of true errors. Thus, if the permissible error rate in the image interpretation is pre-determined, for example 85 - 90%, as suggested by the US Geological Survey Circular 671 (Anderson et al., 1972) or as required in an operational job specification the sample size for each land use category (stratum) necessary for 85% interpretation accuracy should be at least 20, and for 90% accuracy, at least 30. Therefore, by using the table

the minimum sample size required for checking any interpretation accuracy can be determined. It is a minimum because for any smaller sample size even a 'perfect' (i.e., error free ground check) result signifies very little. Tables 3 and 4 provide more detailed calculations of the probabilities of scoring errors in samples of varying sizes with specified interpretation levels of 85% and 90% respectively.

2:2 Sampling Strategy

It has been demonstrated that a minimum sample size of at least 30 is necessary for each land use type in order to meet the US Geological Survey Circular 671 criterion of 90% interpretation accuracy in land use surveys using remote sensing imagery. To locate these 30 points, random point sampling within a land use category (or stratum) can be performed by sampling using random spatial co-ordinates. By this method, each random point is attributed to the interpreted land use type in which it falls until a sufficient number of points has been achieved in all categories. Extra points should be taken in order to ensure adequate coverage caused by the inability to reach a particular site due to unforeseen circumstances.

3. ESTABLISHMENT OF GROUND TRUTH

The structure of the classification scheme, when correctly established, has certain controlling criteria that tend to regulate the scope of the inquiry and determine the accuracy levels to which the imagery should be interpreted, the minimum size of the areal units and other aspects which can affect the nature of the overall ground truth procedure. These difficulties associated with the establishment of a satisfactory ground truth procedure in which the results of the interpretation can be checked in the field were discussed in the preceding sections.

3:1 Sampling Design

The pre-determined sample points are randomly distributed within each category, by placing a large sheet of millimetre graph paper under the base map and using a random number table to generate the co-ordinates of the sample sites. These points are then plotted onto the preliminary land use map. The intersections of lines on the graph paper represent the centres of squares on the ground. The graph paper can be positioned so that the grid references of sites could eventually be transferred to the co-ordinate system used on the topographic maps.

The number of sites for each category was determined by considering the interpretation accuracy level prescribed in the criteria for adopting the classification system, and then by consulting the relevant tables. In practice, the optimum sample size is obtained by the addition of several more sites to the value derived from the tables as certain factors, e. g., bad weather and prohibited access may prevent detail at specific sites from being recorded. Also, the first one hundred sample points are maintained in order to obtain an approximate indication of the distribution of the strata and for the consideration of possible trends after completion of the field work.

Although this method removes much of the subjectivity involved in the allocation of sample sites to each category, it entails the generation of a large number of co-ordinates to be plotted in order to determine the categories into which the points fall. When the desired optimum number of points has been reached for a particular category, no more random numbers are added to the list for that category. Ideally,

random sampling continues until the optimum number is reached for each category. However, in practice, the areal distribution and coverage of some categories may be too small to permit the generation of enough random points. If this occurs several alternatives are available to satisfy the need of an adequate field check. The investigator may visit all the areas in that category whilst field checking other sites, or use the number of sites that were generated after a tolerable period of random sampling and accept the fact that the accuracy level of that particular category may not meet the accepted level required for the survey. If these alternatives are not reasonable, then the classification system may have to be re-adjusted so that the category is subsumed into the next level.

3:2 Analysis of Results

On examination of the ground data collection sheets several sites may have to be excluded due to inaccessibility or misplotting. Then, the sheets for the sites which were incorrectly interpreted are investigated and comments on possible reasons for mis-interpretation listed. On-site photographs are used as additional data sources for isolating causes of the incorrect interpretations. The predominant reasons for mis-classification appears to be the occurrence of a site in a small area of a particular category which is located in a much larger area of another category, the size of the small patch not being large enough to meet the smallest mappable area requirements.

4. CONCLUSION.

A scheme for systematically analysing the results of the interpretation of LANDSAT MSS imagery was successfully devised and tested, in the operational sense, during the production of a land use map of Murcia Province, South East Spain. Although the system was based on the commonly used stratified random strategy, one important aspect was developed in this study involving a method of determining the most appropriate sample size. This technique utilises interpretation accuracy levels that are lower than the normally accepted standards adopted in conventional surveys using air photo-interpretation methods. This situation arises from the concept of incorporating the probability of making incorrect interpretations at particular prescribed accuracy levels, contrasting with the usual practice of expressing the interpretation errors as a percentage of a subjectively derived number of sample sites.

Consequently, it is believed that this approach offers a more meaningful explanation of the interpretation accuracy levels of the whole operation and within each category. Furthermore, it should prove to be very useful in other types of operational remote sensing projects, saving time and money, where stringent specifications need to be met but prior to this study, it was not possible to check the accuracy of the work in any reliable, statistical manner.

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TABLE 1
MATRIX SHOWING HYPOTHETICAL NUMBERS
OF SITES IN ACTUAL AND INTERPRETED
LAND USE CATEGORIES.

LAND USE (on the ground)

LAND USE
(interpreted
from imagery)

	A	B	C	Sum
A	12	1	4	17
B	2	19	0	21
C	1	0	12	13
Sum	15	20	16	51

TABLE 2
PROBABILITY OF SCORING NO ERRORS IN SAMPLES OF VARYING SIZES FROM A
POPULATION WITH A RANGE OF REAL ERROR PROPORTIONS. q .

$\backslash$ A	X	5	10	15	20	25	30	35	40	45	50	60
.99												.547
.95							.215	.166	.129	.099	.077	.046
.90				.206	.122	.072	.042	.025	.015	.009	.005	
.85				.087								
.80			.107	.035								
.70	.168	.028										
.60	.078											
.50	.031											

X = Sample size
A = Specified interpretation accuracy.

TABLE 3
PROBABILITY OF SCORING ERRORS IN SAMPLES OF VARYING SIZES FROM
A POPULATION WITH REAL ERROR PROPORTION OF 85%
i.e. THE SPECIFIED INTERPRETATION ACCURACY LEVEL IS 85%

number of errors (f) sample size	0	1	2	3	4	5
15	.0874					
20	.0388	.1368				
25	.0172	.0759	.1607			
30	.0076	.0404	.1034			
35	.0034	.0209	.0627	.1218		
40			.0365	.0816		
45			.0206	.0520	.0963	
50				.0319	.0661	.1072
55				.0189	.0434	.0781
60					.0275	.0544
65						.0365

— stepped line indicates approximate
.05 level of probability

TABLE 4
PROBABILITY OF SCORING ERRORS IN SAMPLES OF
VARYING SIZES FROM A POPULATION WITH REAL ERROR
PROPORTION OF 90% i.e. THE SPECIFIED
INTERPRETATION ACCURACY LEVEL IS 90%

number of errors (f) sample size	0	1	2	3
15	.2059			
20	.1216			
25	.0718	.1994		
30	.0424	.1413		
35	.0250	.0973		
40		.0657		
45		.0436	.1067	
50		.0286	.0779	
55			.0558	.1095
60			.0393	.0844
65				.0636
70				.0470

— stepped line indicates approximate
.05 level of probability

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PRESENT AND FUTURE OPERATIONAL NOAA SATELLITE

OCEANOGRAPHIC PRODUCTS: AN INTRODUCTION

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ABSTRACT

A review of operational satellite-derived NOAA/NESS oceanographic products is presented and some current applications of these products are noted. Recent improvements to procedures used in deriving sea surface temperature observations and fields are described. Changes to data reduction techniques and products which will be incorporated with the advent of TIROS-N are outlined and some potential future developments are mentioned.

1. INTRODUCTION

The National Environmental Satellite Service (NESS) is charged in part with the development and routine production of oceanographic products derivable from data collected by polar-orbiting and geostationary environmental satellites flown under the auspices of the National Oceanic and Atmospheric Administration (NOAA). These products, both quantitative and qualitative, come in a variety of spatial and temporal resolutions and serve a spectrum of users ranging from the weekend sailor on a pleasure cruise to the research scientist studying long-term climatic changes. In Section 2 of this paper we briefly consider the satellites and instruments currently involved in the remote-sensing of oceanographic data. In Section 3 we survey the products presently produced from these data. In Section 4 we discuss recent improvements in the operational procedures used in the derivation of sea surface temperature (SST) observations and fields. (This section is especially directed to readers already possessing some familiarity with these procedures.) In Section 5 we look at changes in SST products and retrieval techniques which are planned for implementation when the first of the TIROS-N series of polar-orbiting environmental satellites becomes operational in the fall of 1978. Several developmental and potentially operational TIROS-N product capabilities will also be mentioned. In keeping with the spirit of an introductory/review paper, only the broad outlines of processing techniques and applications will be given whenever the specific details of such have been previously published. Appropriate references will instead be cited.

2. CURRENT SATELLITES AND SENSORS

2.1. THE IMPROVED TIROS OPERATIONAL SATELLITE (ITOS)

The last in the current series of ITOS polar-orbiting satellites, designated NOAA 5, has been fully operational since September, 1976. As with other satellites in the series, NOAA 5 is in a near-circular, 102° inclination orbit and completes approximately 12.4 1500-kilometer altitude orbits per day, permitting at least two looks per day (night and day) at each point on the earth. Its sensor complement includes a Solar Proton Monitor, a Vertical Temperature Profile Radiometer (VTPR), a Scanning Radiometer (SR) and a Very High Resolu-

tion Radiometer (VHRR). The SR has two channels, visible and thermal infrared (10.5-12.5 μ m), with about 4.2- and 8.0-km resolutions, respectively. Similar channels in the VHRR both have 0.9-km resolution. The VTPR is an eight-channel atmospheric sounder with six channels in the 15 μ m CO₂ band, one water vapor and one thermal infrared window channel. Further details on the instruments and their functions can be found in Fortuna and Hambrick (1974) and in Schwalb (1972).

2.2. SYNCHRONOUS METEOROLOGICAL SATELLITE (SMS)/GEOSTATIONARY ORBITING ENVIRONMENTAL SATELLITE (GOES)

NOAA presently maintains two operational geostationary satellites, GOES 1 and SMS 2, nominally located at longitudes of 75° and 135°W, respectively, at altitudes of about 35,800 km above the equator. [The satellites are identical, with SMS denoting original NASA sponsorship.] These satellites provide continuous meteorological surveillance of a majority of the Western Hemisphere. The instrument of primary oceanographic significance on each is a Visible and Infrared Spin Scan Radiometer (VISSR). Each VISSR has eight visible and two (redundant) infrared channels and is capable of providing a full-disk image of the earth every thirty minutes. The VISSR visible and infrared channels have 0.8- and 8.0-km resolution respectively. Further details about the SMS/GOES system can be found in Corbell, et al. (1976) and Bristor (1975).

3. PRESENT DAY OCEANOGRAPHIC PRODUCTS

In the following subsections we review the types of oceanographic products now generated by NESS from satellite data. For ease of treatment they are divided into groups according to the sensor(s) from whose data they are generated.

3.1. PRODUCTS FROM SR (AND VTPR) DATA

3.1.1. GLOBAL SST OBSERVATIONS

The main quantitative oceanographic product available today is 100-km resolution SST observations obtained from the automated Global Operational Sea Surface Temperature Computation (GOSSTCOMP) computer procedure. Observations are produced from target arrays of SR infrared data, evaluated for cloud contamination, corrected for atmospheric attenuation, and then quality controlled. VTPR data are used in these procedures when available; otherwise, empirically derived corrections are applied. The overall reduction technique is as described in Brower, et al. (1975) and Brower, et al. (1976), except for those changes described in Section 4 below and first detailed in Walton, et al. (1976).

About 4000 highest quality SST measurements and about 10,000 of all qualities are produced daily. All SST measurements for a given month are retained on computer disk and then archived for the Environmental Data Service through which they are made available to users; for example, researchers of topics involving climatic trends or SST anomaly studies. Each day a tape of SST observations is supplied to the U.S. Navy for use in its Fleet Numerical Weather Center SST field analysis. Interested parties with access to the NOAA computer can obtain lists of the current day's observations via remote terminal.

3.1.2. GLOBAL SST FIELDS

Each day the Objective Analysis Technique (OAT) of the GOSSTCOMP procedure merges new SST observations into the global 256 by 512 point polar-stereographic SST field. The OAT uses numerical techniques to weight and blend new observations into the regularly spaced field which is accessed daily by the National Meteorological Center for use in its numerical weather forecasts. Remote terminal and batch access to obtain latitude-longitude grid printouts of the field are possible. Weekly the global field is contoured, and mercator and polar-stereographic maps of sea surface isotherms are produced for distribution to a world-wide list of users. The SST field temperatures are also used as a set of boundary conditions in the production of atmospheric temperature profiles from VTPR data (McMillin, et al., 1976) and the National Marine Fisheries Service (NMFS) in La Jolla, California refers to this product in preparing infor-

mation useful to the Pacific tuna fleet. Another user is the National Hurricane Center in Miami, which utilizes the SST field in their hurricane watch. Every ten days, ten day's of fields are archived for the Environmental Data Service and made available in tape format to requesting users.

Changes to the OAT which have been implemented since the publication of Brower, et al. (1976) are discussed in Section 4 below.

3.1.3. MONTHLY MEAN SST ANALYSIS

Monthly contour charts of mean SST are being made available to interested users. This new product is produced from averages of all SST observations falling in each square of a 64 by 64 grid overlaying a polar-stereographic map base for both the Northern and Southern Hemispheres. Accompanying these mean SST charts is a second pair of contoured displays showing the number of observations incorporated into each mean temperature grid value. This product should be valuable as an anomaly and climatic change analysis tool.

3.2. PRODUCTS USING VHRR AND VISSR DATA

Oceanographic products employing the high resolution data of the VHRR and VISSR are primarily qualitative in nature and most often in the form of or derived from enhanced imagery. Products have their greatest utility in the depiction of relative temperature differences, although absolute calibration using external sources of data is possible.

3.2.1. OCEAN THERMAL FRONT ANALYSIS

3.2.1.1. PRESENT WEST COAST APPLICATIONS

VHRR infrared images received during cloud-free periods are used to produce charts depicting the location and character of thermal fronts off the coast of California. Special image display techniques enhance differences in ocean surface temperature and identify sites where upwelling of cold water is occurring. The primary use of this information is in fishery analysis because the upwelling carries nutrient-rich water to the surface and creates favorable sites for the feeding of large schools of fish. Fishing fleets; e.g., those seeking salmon and tuna, often find these sites equally favorable. This product is disseminated by the Satellite Field Service Station (SFSS) in San Francisco. See Stumpf (1975) and Strong, et al. (1972) for further information on the applicability of satellite data to studies of upwelling.

3.2.1.2. EAST COAST APPLICATIONS

The Gulf Stream can be readily seen in cloud-free VHRR infrared (IR) imagery. Identifiable features include warm and cold eddies, continental slope and shelf water masses and thermal fronts such as the Gulf Stream North Wall (the region of steepest temperature gradient separating the slope water from the Stream and paralleling the highest velocity portion of the Stream). Each week the latest cloud-free VHRR IR images are used to produce a Gulf Stream Analysis available by National Facsimile and by mail. GOES VISSR IR imagery is also utilized in this analysis since it is obtained more frequently and provides an improved chance for a cloud-free look. Using these charts, mariners can save time by navigating in the Stream (with the current) when northbound, and by avoiding it when southbound. The charts are useful to the Coast Guard for search and rescue missions, as well as to yacht racers, fishermen and oceanographers. A related product is the Gulf Stream Wall Bulletin, which is broadcast three times a week by the Coast Guard and contains latitude and longitude coordinates of points along the Wall. See Stumpf (1974) and Baig (1976) for further information.

3.2.2. EXPERIMENTAL THERMAL GRADIENT ANALYSIS

An experimental product derived from GOES data currently displays thermal gradients in the Gulf of Mexico and along the eastern coast of the U.S. using a dynamic computer processing technique. Several times per day, VISSR visible

channel data for the region are ingested and tested against a brightness threshold to identify and eliminate obviously obscured areas from further consideration. Infrared data for the remaining, apparently clear, areas are temperature calibrated and then compared, sample for sample, against corresponding data from previous looks for the same day. By means of a compositing maximum temperature replacement procedure additional cloud- or haze-obscured data are eliminated and a multi-look array of the underlying ocean thermal structure is obtained. The end result is a daily display which is as completely free as possible of clouds. The technique allows thermal gradients in the Gulf of Mexico Loop Current, the Gulf Stream and in smaller features to be studied. An absolute temperature calibration using external sources of data is also possible. See Miller, et al. (1977) for additional details.

3.2.3. EXPERIMENTAL LOOP CURRENT AND GULF STREAM MOVIE LOOPS

Another experimental research tool utilizing the multi-look capabilities of the GOES sensors consists of infrared images sequenced in movie form and covering relatively long-periods (days) of time. These movies are capable of revealing motions in the Loop and Gulf Stream Currents and are suited to analyses of their dynamics (Legeckis, 1975).

3.2.4. ICE ANALYSES

Three ice analyses are produced routinely from VHRR (IR and visible) and GOES (visible) data.

The Great Lakes Ice Analysis is produced twice weekly during the winter months from satellite imagery. The end product is a chart depicting the location and thickness of ice on the Great Lakes. It is used by the Coast Guard as an aid to navigation and by the National Weather Service (NWS) for ice forecasting.

A Polar Ice Analysis of ice concentration and coverage is made weekly for the seas bordering Alaska. It is used for navigation, ice forecasting (by the Navy as well as the NWS) and as an aid to oil exploration expeditions. The Labrador Sea Ice Analysis is similar to the Polar Ice Analysis.

In addition to the above products, further applications of satellite data to ice studies have been investigated on a limited research basis because of the climatic influence of Arctic and Antarctic ice cover. Information pertaining to this work and to the above analyses can be found in McClain (1974) and in McMillan and Forsyth (1976).

4. RECENT IMPROVEMENTS IN SST OPERATIONAL PROCEDURES

Despite the rapid progress of the last several years, the science of deriving environmental parameters from satellite observations is still in its childhood. The science is, consequently, very dynamic, and will hopefully continue to be as long as the improvements and benefits reaped from change promise to overshadow the costs of modifications.

4.1. ADOPTION OF A NEW DATA REDUCTION AND CLASSIFICATION PROCEDURE FOR SST OBSERVATIONS

Since late April 1976, a new technique for the evaluation of SST targets with regard to their cloud contamination, if any; their correction for atmospheric attenuation; and the classification of observations as to quality has been part of the GOSSTCOMP procedure. The technique has been fully detailed in Walton, et al. (1976), which supersedes the corresponding parts of Brower, et al. (1976) as a description of the steps taken in target analysis and SST observation production. We outline its main features below.

The backbone of the present procedure is a set of classification criteria based on (1) a comparison of the SST target scene temperature derived from SR data [via the mean estimate histogram (MEH) technique discussed by Brower, et al. (1976)] with the higher resolution target temperature observed in the IR window channel of the VTPR, and (2) a comparison of this second temperature

with the temperature seen by the $13.38\mu\text{m}$ CO_2 channel of the VTPR (the CO_2 channel which penetrates furthest into the earth's atmosphere). The classification scheme evaluates the degree of contamination of each VTPR measurement relative to that of the coincident SR-derived SST target and categorizes it as either clear, mildly contaminated or grossly contaminated. The first comparison identifies targets in which the scene temperature is discontinuous due to non-uniform cloud cover--in which case, the SST target should be warmer than the VTPR window channel temperature. The second comparison distinguishes the ocean surface from a uniform cloud layer. This is possible because a correlation exists between the degree of cloud cover and the IR window - CO_2 channel temperature difference. For a uniform cloud layer the two temperatures converge.

As noted above, three classes of SST measurements emerge from the procedure. A careful evaluation of the technique indicates that its success is such that "Class 1" SST measurements can be adopted as valid observations (after correction for atmospheric attenuation), subject only to a coarse "neighbor check" involving a weighted comparison with adjacent measurements. There is no further quality control of these data; specifically none involving their comparison with the existing (day-old) SST field or with climatology. Further quality control is performed, however, before "Class 2" or "Class 3" measurements are adopted as SST observations. The current procedure is reviewed in the next subsection.

Atmospheric attenuation corrections to Class 1 and 2 SST measurements are now determined using a mathematical expression whose coefficients have been derived by a multiple linear regression procedure. The variables entering the expression are the SST of the existing field and the scene temperature measured by the water vapor channel of the VTPR. Since the effect of cloud contamination of the VTPR measurements is to overestimate the attenuation calculated via this algorithm, it is not employed for Class 3 measurements. They are corrected using a simple regression equation which is a quadratic function of the existing field SST.

The present procedure for obtaining SST observations has yielded an increase in their total number of more than forty percent. Moreover, the new technique yields data which agree better with SST's measured by ships than did formerly-derived satellite SST's. This is primarily because of the increased accuracy of Class 1 observations.

4.2. MODIFICATIONS TO THE GOSSTCOMP OAT

Accompanying the April 1976 changes discussed in Subsection 4.1 were four modifications to the OAT used in construction and maintenance of the global SST field. These supplant parallel procedures described in Brower, et al. (1976) and are summarized next.

(1) The practice of modifying the SST field with climatological data to account for seasonal changes in areas where poor weather prohibits satellite observations was abolished. This practice tended to reduce true SST gradients; e.g., in the Gulf Stream, and the increase in the number and quality of observations provided by the new data reduction and classification procedures mitigated its usefulness.

(2) The procedure used in blending new observations into the field was changed. Grid point temperatures are now altered using a weighted (according to class) mean of all observations within the search area surrounding the point. This change tends to reduce the magnitude of false (but also of true) gradients in the field.

(3) The maximum-allowed 24-hour change in a field temperature was increased to allow for faster field recovery following persistent cloudiness. It is presently set at two degrees per day.

(4) The maximum distance about a grid point in a low gradient area which is used in searching for new observations was reduced by one-third. It is now 400 kilometers.

The results of these changes are a reduction in the number of point anomalies in low-gradient areas and a better representation of steep gradients. The improvement in the agreement of satellite-derived observations and ship reports resulting from the new data reduction and classification procedures is better reflected in the SST field.

The winter of 1976-77 more than amply illustrated the inability of present-day NOAA satellites to monitor surface parameters through persistent cloud cover. Long periods of cloudiness in the Western Atlantic and Western Pacific, coupled with the elimination of climatology from the GOSSTCOMP procedure allowed the portions of the SST field including the Gulf Stream and the Kuroshio Current off Japan to first become badly outdated and inaccurate, and then self-sustaining. This latter problem was due to a lack of Class 1 observations and the rejection of Class 2 and 3 data by the field comparison quality control check. Analysis of the problem resulted in additional OAT modifications which are now operational. These changes described below, permitted a faster recovery in the problem areas and will, hopefully, prohibit or at least retard a recurrence of this weather-induced condition.

(1) Class 1 observations, as compared to other types, have been given much greater weight in the analysis. This has the effect of making the weight (i.e., reliability) assigned to a field point in a data sparse area comparatively very low if no, or only Class 2 and 3, observations have been available. When Class 1 observations are available along with Class 2 and 3 data, the latter have almost no effect on the field. The retrieval of a Class 1 observation acts to rapidly rejuvenate an outdated field.

(2) Quality control of Class 2 and 3 measurements is now made via a comparison with climatology, instead of one with the existing field. This comparison is very much less restrictive than it was formerly (to avoid too great a bias toward climatology). A poor field will no longer cause a measurement to be rejected as an invalid observation.

(3) There is no longer an iteration of the neighbor-check procedure which uses nearby measurements, and the tolerances for this check are less restrictive than in formerly employed techniques. Its main function is now the elimination of gross errors, whereas it was previously a restrictive test applied in the hope of eliminating cloud-contaminated data.

Overall, changes reflect greater confidence in Class 1 observations, with a corresponding reduction of quality control which facilitates more rapid SST field evolution. In the absence of Class 1 data, Class 2 and 3 observations--with their inherent shortcomings acknowledged--can now maintain a data sparse field closer to truth.

5. THE FUTURE WITH TIROS-N

The launch of TIROS-N in 1978 will initiate a new satellite and data processing system designed to carry the NESS mission through the mid-1980s. Some details of the TIROS-N system have been discussed by Ludwig (1974a; 1974b). Initially the instrument package on the new satellites will include a 4-channel (one visible, one reflected-IR, two thermal-IR) Advanced Very High Resolution Radiometer (AVHRR) and a second generation 20-channel High Resolution Infrared Radiometer Sounder (HIRS/2). A fifth channel, also in the thermal-IR, is planned for later versions of the AVHRR. The new satellites will move at altitudes of about 830 km in near-circular polar orbits of 102° inclination. Each will complete about 14.2 orbits per day. Operationally, TIROS-N is a two satellite system employing satellites whose orbital descending nodes are spaced about 60° in longitude.

A number of changes from present day procedures are projected for the TIROS-N SST processing system. Some of the more significant are as follows:

(1) The resolution of an average SST observation will increase to about 50-km.

(2) It is estimated that 40,000 or more Class 1 observations will be obtained per day per spacecraft. This is a factor-of-ten increase over today's situation. It may no longer be necessary (or reasonable) to process Class 2 or 3 data.

(3) A maximum-likelihood technique (described by Crosby, 1975) for determining the clear-scene temperature from an array of AVHRR data will replace the MEH technique now employed.

(4) AVHRR SST targets will all be centered upon HIRS/2 sounding targets. This will increase the comparability of data from the two instruments, and, when desired, will actually result in an oversampling of the AVHRR data. The partial use of the same AVHRR data in analyzing adjacent targets will, in low-gradient areas, greatly facilitate a determination of errors internal to the instrument and processing systems. Thus, an estimate of the errors inherent in satellite SST determinations which is independent of "ground truth" data (e.g., ship reports which are themselves subject to errors) may become possible.

(5) All SST fields will be maintained as latitude-longitude arrays rather than polar-stereographic arrays.

The increased capabilities of TIROS-N will result in improved present-day products and in several new ones. Three of these are described next.

(1) Movable 2500 square-degree meso-scale SST fields having 50-km resolution will be maintained in selected areas. Initially, at least, they are expected to encompass the U.S. 200-mile Conservation and Management Zone.

(2) A global 500-km resolution climatic-scale field on a 5° grid will be maintained in support of climatological studies.

(3) Full resolution digital data from the AVHRR will be used to prepare weekly hand-drawn isothermal analyses of the Great Lakes and the U.S. Coastal Zone. These will have obvious fishery, shipping and weather forecasting applications. (See Strong, 1974 for experimental examples.)

Candidates for future experimentation with TIROS-N data include research into the feasibility of multichannel AVHRR-only retrieval techniques. If a successful procedure can be developed, it may become possible to produce even higher resolution (perhaps 10 km) SST observations having acceptable accuracies. Oceanographic product experimentation may include the development of temperature change charts and anomaly charts. Improved techniques will facilitate the long-term development of a global satellite-derived oceanographic climatology. Such a climatology would have the unique advantage of having been derived from a minimal number of intercomparable instruments. The development of an increasing number of oceanographic products and data bases is foreseen.

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POLARIMETER MEASURES SEA STATE CHARACTERISTICS USING

EMITTED INFRARED RADIATION

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ABSTRACT

An infrared polarimeter, capable of operating between 1 and 12 micrometers wavelength has been used to measure the polarization of emitted radiation from the sea. The observed polarization at 10.6 micrometers from a smooth sea was found to be positive, indicating the dominance of reflected infrared sky radiation over the emitted. With the appearance of waves, the percent polarization increased, as expected, for a zenith angle well above the Brewster angle for water. This is qualitatively in accordance with a model presented to explain the behavior. Initial analyses indicate that the polarized components of the sea's emitted and reflected radiation are affected by type and direction of waves, angle of viewing, and foam. The effects of variations in these parameters require further delineation. The infrared polarimetric technique appears to be a novel new passive method for remote monitoring of waves.

INTRODUCTION

The global distribution of sea state is of great interest because it determines local ocean and coastal processes, and is indirectly an indicator of the wind field above the sea. The sea state also is affected by surface flotsam, such as oil slicks, and thus has an environmental interest.

Present techniques for remotely measuring sea state include passive microwave radiometry, radar scatterometry, and laser altimetry. We have developed a new system that indicates the wave height by means of the polarization of the sea's emitted and reflected infrared radiation.

It has been recognized for a long time that the emitted radiation from surfaces is polarized. In 1895 R. A. Millikan published two papers explaining the polarization of light emitted by incandescent solid and liquid surfaces. Earlier, Arago (1824) had shown that light from incandescent solids and liquids was partially polarized. Solids need not be highly heated in order to emit polarized radiation. Solids at room temperature emit infrared radiation peaking near 10 micrometers wavelength; their radiation also would be expected to be polarized and this fact was confirmed with experiments by Sandus (1965).

The emitted radiation from bodies of water, in the wavelength range from 2 to 200 micrometers wavelength appears to be polarized (Hall, 1964). In scanning from the nadir to the horizon Clark and Frank (1963) observed a decrease in the apparent radiometric temperatures of the sea. Hall (1964) used a theoretical analysis based on Fresnel's equations to show that this decrease is caused by the emitted radiation from a calm sea being polarized.

Because the emission of polarized radiation has been established, there arises the question as to whether surface roughness (such as sea state) can affect the polarization. Roughness of solid surfaces was found to decrease polarization (Sandus, 1965). Thus, the polarization of the emitted infrared radiation would be expected to decrease with sea surface roughness (wind waves or foam).

We first consider the emitted polarized radiation from the sea, and then consider the effect of polarized reflected infrared sky radiation reflected from the sea.

A theoretical investigation has been conducted of the effect of crosswind speed (causing waves) on the polarization of infrared light emitted by the sea (Basener and McCoyd, 1967). The results of their analyses are presented in Figs. 1 and 2, for 12.6 μ m and 8.5 μ m, which are chosen above and below the maximum infrared emission wavelength of 10 μ m. These wavelengths were selected to illustrate the effect of a variation in absorption coefficient. The polarization increased with nadir angle and absorption, but decreased with wind speed. Since wind speed is related to wave height for a given fetch (Fig. 3), wave height is related to the polarization of the sea's emitted radiation.

The basis of the polarization effect of the emitted radiation from the sea can be understood by referring to Fig. 4. These curves present typical results of a theoretical investigation by Hall (1964) for the parallel and perpendicular components of 12.6 μ m emitted radiation as a function of emission angles. These curves are calculated using the optical complex index of refraction of water at 12.6 μ m. The published values of the infrared optical complex indices of refraction are similar between authors (Irvine and Pollack (1968); Kislovskii (1959)). The values used in the present calculations are close to those published. At normal viewing, the apparent emission temperature for both the parallel and perpendicular components of emitted radiation is about 270°K. The actual sea temperature (T_w) is assumed to be 280°K and the air above it (T_s) at 290°K. (The parallel and perpendicular components refer to the direction of vibration of the electric vector relative to the plane formed by the emitted ray direction and the nadir.) The percent polarization is given by the relation:

$$\% \text{ Polarization} = 100 \times (E_{\parallel} - E_{\perp}) / (E_{\parallel} + E_{\perp})$$

where:

$E_{\parallel}$ = Intensity of the parallel component of emitted infrared radiation

$E_{\perp}$ = Intensity of the perpendicular component of emitted infrared radiation

At 12.6 micrometers wavelength, the percent polarization shown in Fig. 1 may be calculated from the curves of Fig. 4 for smooth water. (The negative sign for polarization signifies that the dominant electromagnetic wave vibration is parallel to a plane defined by the emitted ray and the surface normal.)

A water wave can be modeled as shown on the inset of Fig. 4 using small facets on the wave tilted at various angles to the viewing direction. These individual facets still emit polarized radiation relative to their local normal in accordance with the curves of Fig. 2. However the projected area of these facets is such as to emphasize the lower local nadir angles. In effect the curves of Fig. 4 are displaced to the right, shown qualitatively as the dashed curves, decreasing the percent polarization. An exact representation

depends upon the model of the facet distribution. The results of using the Cox and Munk (1954) crosswind wave distribution are as shown in Figs. 1 and 2. For upwind or downwind, there is a small difference in the probability distributions of the water waves, and the crosswind components are generally smaller than the upwind mean square slope components. This, if an upwind wave distribution were used to calculate Figs. 1 and 2, a greater depolarization would be expected for the same corresponding wind velocities.

When foam occurs, the brightness temperature of the perpendicular and parallel components is equal and independent of viewing angle (Fig. 4).

As a prelude to describing the effect of reflected infrared sky radiation from the sea, there will be a reflected parallel component of infrared radiation from the water shown in Fig. 4. The amount of reflected radiation will depend upon how high the sky temperature is. The reflected radiation will generally contribute to both the parallel and perpendicular emitted components, with the perpendicular component contribution dominating. This will result in positive polarization of the emitted radiation, from reflection.

We again may use the results of Hall (1964) to calculate the polarized components of reflected infrared radiation from the sea at $12.6\mu\text{m}$, for instance. The results are presented in Fig. 5 as a function of reflection angle (equals the incidence angle) for the two components in terms of the components shown on Fig. 4. The intensities are normalized in order to show relative effects. The calculated percent polarization by using Fig. 5 is presented in Fig. 6 for smooth water; the polarization is seen to be positive with a peak of 94.4% at the Brewster angle (53°).

When waves perturb the surface of the water, the percent polarization will increase for emission angles above the Brewster angle (the amount of increase will depend upon the emission angle and the wave height). However, below and at the Brewster angle, the polarization will decrease. The approximate effect of surface roughness from waves is schematically shown as the dashed curve in Fig. 6.

A similar polarization curve occurs (Fig. 7, solid curve) at 8.5 micrometers wavelength where the water is much less absorbing (i.e. the optical complex index of refraction is $1.28-i0.051$). Now, because of the low absorption, the peak polarization is almost 100% at 53° . Here the effect of surface roughness from waves is schematically shown as the dashed curve.

At the Brewster angle, and at larger angles, the sea surface strongly reflects the sky radiation, which in general may be at a temperature different from the sea. When the sky temperature is greater than the sea (as when an aerosol layer exists), the magnitude of the reflected perpendicular component will increase (Fig. 4), and decrease the polarization at the Brewster angle. When the water is more absorbing, perhaps because of pollutants, the surface reflection is greater, producing stronger positive polarization. Thus, we see that the polarized infrared emitted radiation from the sea is dependent upon the sea's emitted as well as reflected infrared radiation. The disentangling of the two variables requires a knowledge of the sky infrared background, as a function of elevation angle and azimuth, as well as the measurement of the polarized components of the infrared radiation from the sea as a function of azimuth and elevation angle. For large emission angles, the polarization observed on a warm summer day would be expected to be positive ($T_s > T_w$), and the percent polarization would be expected to increase with increase in wave height. However on a cold, clear winter day ($T_s < T_w$), the percent polarization near the Brewster angle would be expected to be negative with a decrease from increase in wave height.

The water and sky temperatures are remotely observed using the brightness sensed by the polarimeter for the perpendicular and parallel polarized components, and this permits disentangling the variables.

A polarization difference of $\pm 0.1\%$ should be resolved with a good polarimeter, and depending upon observational conditions, wave heights of at least a few centimeters could be resolved. Further, the transition between wave heights would be discerned passively, night and day. There is no requirement that the sea waves be highly correlated, and confused seas should be equally well discerned.

Solid cloud cover will not be penetrated by infrared emission, but the long wavelength infrared emission is highly effective in penetrating haze because of reduced scattering, although this is to some extent counterbalanced by increased emission from the atmosphere. The infrared polarimeter approach is not limited to vertical incidence, but sensitivity increases with increase of viewing angle from normal incidence.

INFRARED POLARIMETER SYSTEM

The present optical configuration for the infrared emission polarimeter is shown in Fig. 8, the actual implementation in Figs. 9 and 10, and the associated electronics block diagram in Fig. 11. The entrance optics (Fig. 8) consists of a 39mm diameter, 63 mm focal length KRS-5 lens that passes infrared radiation between 1 and 40 micrometers wavelengths, followed by an aperture to restrict the acceptance angle to 1° . Reflective optics are generally undesirable for polarimeters even though they achieve large light gathering with a minimum of emission by the elements. Reflective optics may be critical in alignment because most optical elements, while having the right curvature, may not have their center of symmetry exactly along their geometrical centers. This displacement of the true axis can cause extraneous polarization to be introduced into the optical system. The field stop (Fig. 8) may be chosen to limit the system field of view from 1 degree to 1 minute of arc; a one degree field of view is appropriate for most low altitude observations; a one minute field of view would yield a sea level resolution element of about 200 meters for a satellite at an altitude of 1000 km. The radiation is chopped at a frequency of 450 Hz (nonmultiple of the power line frequency) to minimize interference from line frequency noise, with the reference being the reflected radiation from the housing by the gold plated rear chopper surface. The polarization analyzer is a wire grid rotating at a speed of 6.9 Hz (also a nonsubmultiple of the power line frequency). All lenses are KRS-5. A specially designed multipositional cryostat is used so that when the system is flown in an aircraft, or views the sky, the cryostat will maintain the detectors in a cooled condition. The interference filter in association with the Si:As detector determines the sensed wavelength and bandwidth. The aperture stop serves to limit the majority of the rays to near axial. With the use of large field stops, this is necessary for proper bandwidth limitation on the interference filters and for effective operation of the polarization analyzer.

The optical system is about 50 cm long. The major assemblies can be seen in Fig. 9, corresponding to those elements indicated in Fig. 8.

The electronic assembly (seen in Fig. 10) is a straightforward combination of readily available units (Fig. 11). The infrared signal from the detector consists of an intensity signal (450 Hz) amplitude modulated by the polarization component at 6.9 Hz. Phase sensitive detection of both signal components is accomplished by the Princeton Applied Research Model 124 and 129 phase sensitive detectors. The low pass filter in the PAR 124 detector

filters out the 450 Hz and 6.9 Hz signals, and the output to the three-channel Recorder is proportional to infrared signal radiance. The PAR Model 129 Phase/Vector Lock-In Amplifier detects the polarization vector of the signal and resolves it into components about a reference direction (which may be recorded).

This approach has the advantage of determining the plane of polarization, when it is not apparent from geometrical considerations. It is not anticipated that the sea would have significant circular polarization, which would require another modification.

MEASUREMENTS AND DISCUSSION

Initial tests of the system at Great South Bay, Long Island, showed that the emitted radiation from the sea indeed was polarized, and that the polarization varied with wave height (and wind velocity). The chopper was at sky temperature (299°K.) At a nadir angle of 83.5°, the relative polarization (chopper temperature reference) was +15%, and a wind velocity of 3 meters/second caused the relative polarization to increase to +50%. The statistical variation of these observations was of the order of +20%, -25%. For this condition, the radiation reflected from the sky dominated that emitted by the sea (i.e. Figs. 5, 6 and 7). At angles above the Brewster angle (i.e. such as 83.5°), the polarization would be positive and increase strongly with increased wave height, as observed. If the polarization were calculated relative to the true zero (i.e. a zero degree K. reference), the percent polarization would be only a fraction of a percent. By having the reference (the chopper blade) near the temperature of the sea, the measurement of polarization is essentially offset from zero, and the relative polarization becomes quite large.

The observations at Great South Bay, Long Island, were made under intermittent gusty wind conditions; in other words, capillary waves occurred (with slopes as large as 1 to 7), and these would decay to gravity waves of lesser slopes. The more steeply sloping capillary waves would be expected to depolarize more strongly than gravity waves, but this remains to be verified, along with the detailed effects of sea surface roughness, direction of waves, angle of viewing and foam.

An infrared emission polarimeter thus appears capable of resolving and measuring wave roughness. A comparison is now made to other approaches.

Passive microwave radiometry as a means for sensing the ocean surface is discussed by Hollinger (1971), with experimental results between 1.41 and 19.34 GHz. It is observed that the microwave brightness temperature of the ocean is significantly dependent upon the surface wind field which causes ocean surface roughness; this ocean surface roughness affects the horizontal polarization of the emitted radiation at larger incidence angles. The problem with passive microwave radiometry is the requirement for extremely large antenna arrays for high spatial resolution from space. In contrast, polarimetric radiometry, in the infrared, can achieve this resolution with small entrance apertures. The infrared polarimeter is related to microwave radiometry with the advantage of high spatial resolution, but with the disadvantage of decreased ability to penetrate cloud cover.

The use of radar altimetry to measure ocean height is discussed by Yaplee et al. (1971). They describe a one-nanosecond (x-band) radar (which is applicable in principle, to a fast pulsed laser); the reflected pulse is unfortunately quite broad, and has a positive time shift resulting from increased reflectivity from the wave troughs. The shift is negligible for

wave heights below 2 feet, but can cause an inaccuracy equivalent to 10 cm for wave heights above 6 feet. A major problem with the laser and microwave altimetry systems is that they are limited to the area directly beneath the sensor. Other problems are high power requirements, large microwave antenna systems, and nonpenetration of cloud cover by the laser reflection.

The radar scatterometer approach described by Krishen (1971) indicates that at 13.3 GHz the backscatter is wind dependent, resulting from the change in small scale structure of the sea. However, the problems of antenna size for adequate resolution and problems in achieving a high signal to noise ratio from space make this approach questionable.

The above described active systems have a considerable power, size, and data handling requirement which does not accrue to the infrared polarimeter. The polarimeter becomes more sensitive at large nadir angles, whereas the altimeters exhibit the reverse behavior.

CONCLUSIONS

The principle of emitted polarized infrared radiation being related to wave height has been demonstrated. However there still remains an extended verification and modeling program to validate the observations under varying wave conditions, weather conditions, and wind conditions as a function of emission angle, observational direction and sensed wavelength. Initial measurements should be made from a stable platform, such as an oceanographic tower, and when such a program is completed, the system may be adapted to aircraft or satellites.

Concurrently, the effect of sea temperature, salinity, contaminants and oil slicks would be investigated as well as the sky infrared background.

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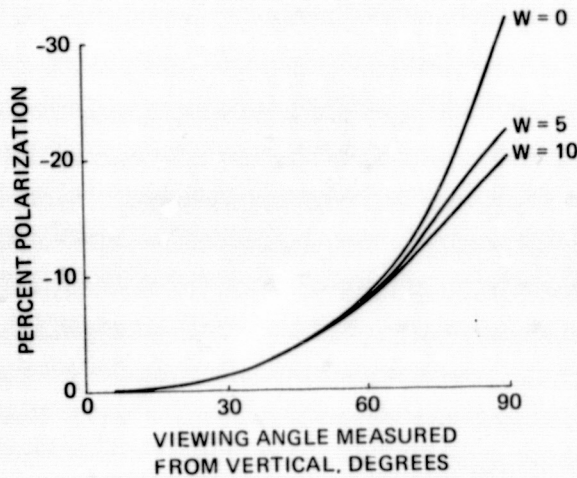


FIG. 1 PERCENT POLARIZATION OF LIGHT
EMITTED BY THE SEA $n = 1.28 - i .294$;
 $\lambda = 12.6 \mu$; W = WIND SPEED IN M SEC⁻¹

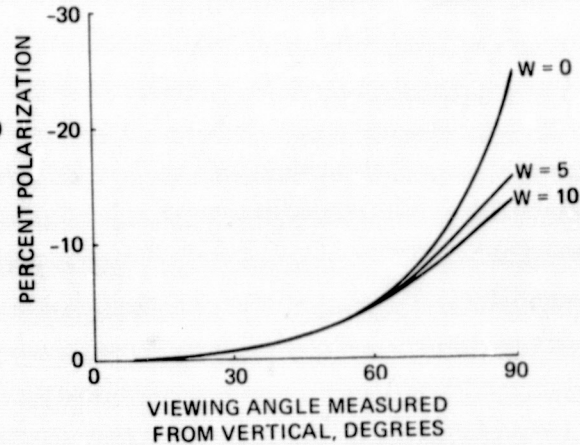


FIG. 2 PERCENT POLARIZATION OF LIGHT
EMITTED BY THE SEA $n = 1.28 - i .051$;
 $\lambda = 8.5 \mu$; W = WIND SPEED IN M SEC⁻¹

I WIND VELOCITY KNOTS	4	5	6	7	8	9	10	20	30	40	50	60	70	II				
2 BEAUFORT WIND AND DESCRIPTION	1 LIGHT AIR	2 LIGHT BREEZE	3 GENTLE BREEZE	4 MODERATE BREEZE	5 FRESH BREEZE	6 STRONG BREEZE	7 MODERATE GALE	8 FRESH GALE	9 STRONG GALE	10 WHOLE GALE	11 STORM							
3 REQUIRED FETCH IN MILES	FETCH IS THE NUMBER OF MILES A GIVEN WIND HAS BEEN BLOWING OVER OPEN WATER																	
4 REQUIRED WIND DURATION IN HOURS	DURATION IS THE TIME A GIVEN WIND HAS BEEN BLOWING OVER OPEN WATER																	
IF THE FETCH AND DURATION ARE AS GREAT AS INDICATED ABOVE, THE FOLLOWING WAVE CONDITIONS WILL EXIST. WAVE HEIGHTS MAY BE UP TO 10% GREATER IF FETCH AND DURATION ARE GREATER																		
5 WAVE HEIGHT CREST TO TROUGH IN FEET				1	2	3	4	5	6	8	10	15	20	25	30	40	50	60
6 SEA STATE AND DESCRIPTION	1 SMOOTH		2 SLIGHT		3 MODERATE		4 ROUGH	5 VERY ROUGH	6	7	8	9	10	11	12	13	14	PRECIPITOUS
7 WAVE PERIOD SEC.	1	2	3	4	5	6	8	10	12	15	20	25	30	40	50	60	70	
8 WAVE LENGTH FEET		20	40	60	80	100	150	200	300	400	500	600	800	1000	1400	1800	2000	
9 WAVE VELOCITY KNOTS		5	10	15	20	25	30	35	40	45	50	55	60	70				
10 PARTICLE VELOCITY FEET/SEC.		1	2	3	4	5	6	8	10	12	14	16	18	20				
II WIND VELOCITY KNOTS	4	5	6	7	8	9	10	20	30	40	50	60	70					

WARNING: Presence of swell makes accurate wave observations exceedingly difficult.

NOTE: (a) The height of waves is arbitrarily chosen as the height of the highest 1/3 of the waves. Occasional waves caused by interference between waves or between waves and swell may be considerably larger.
 (b) Only lines 7, 8, and 9 are applicable to swell as well as waves.
 (c) The above values are only approximate due both to lack of precise data and to the difficulty in expressing it in a single easy way.
 (d) Below the surface the wave motion decreases by 1/2 for every 1/9 of a wave length of depth increase.
 (e) Observations and comments leading to increased accuracy and usefulness are desired.

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FIG. 3 WIND WAVES AT SEA

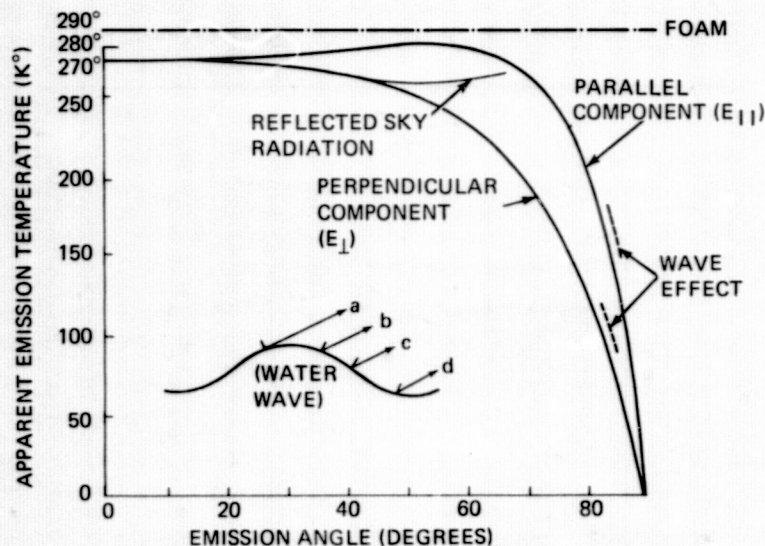


FIG. 4 POLARIZED COMPONENTS OF INFRARED RADIATION EMITTED BY THE SEA AT $12.6 \mu\text{m}$; $n = 1.28 - i 0.294$

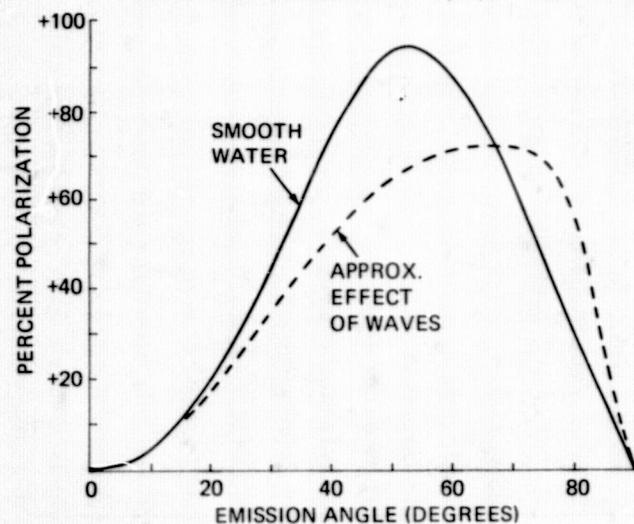


FIG. 6 PERCENT POLARIZATION OF INFRARED RADIATION REFLECTED BY THE SEA; $n = 1.28 - i 0.294$; $\lambda = 12.6 \mu\text{m}$

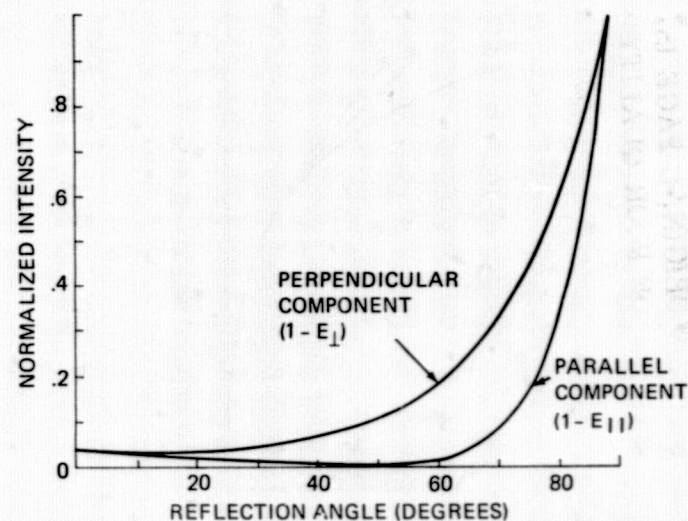


FIG. 5: POLARIZED COMPONENTS OF INFRARED RADIATION REFLECTED BY THE SEA AT $12.6 \mu\text{m}$; $n = 1.28 - i 0.294$.

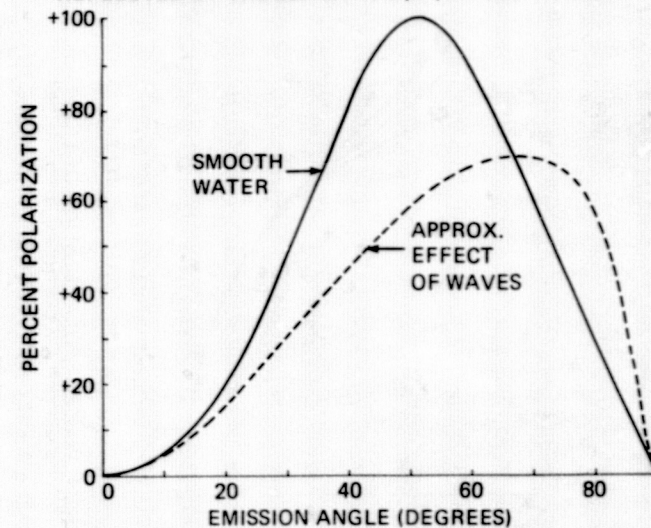


FIG. 7 PERCENT POLARIZATION OF INFRARED RADIATION REFLECTED BY THE SEA; $n = 1.28 - i 0.051$, $\lambda = 8.5 \mu\text{m}$

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OF POOR QUALITY

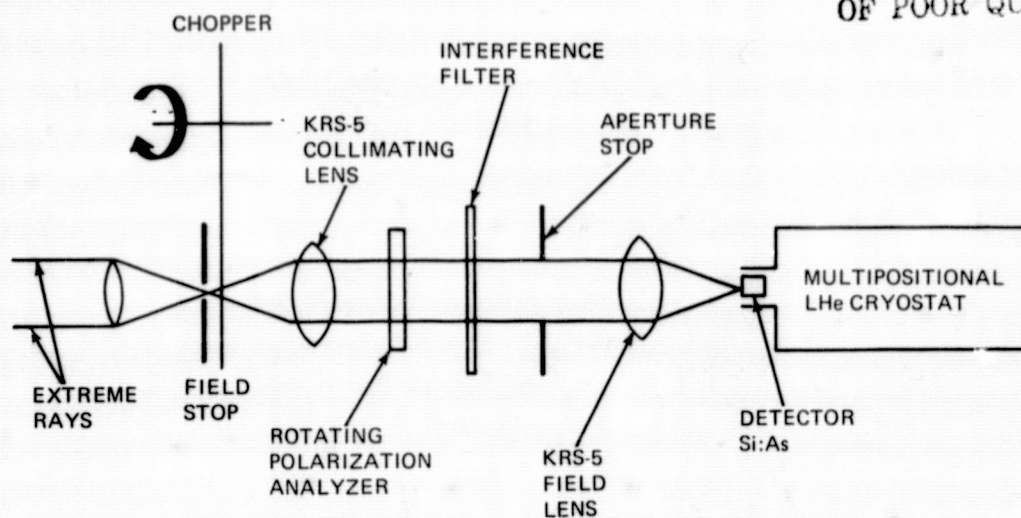


FIG. 8 INFRARED EMISSION POLARIMETER: PRESENT OPTICAL CONFIGURATION

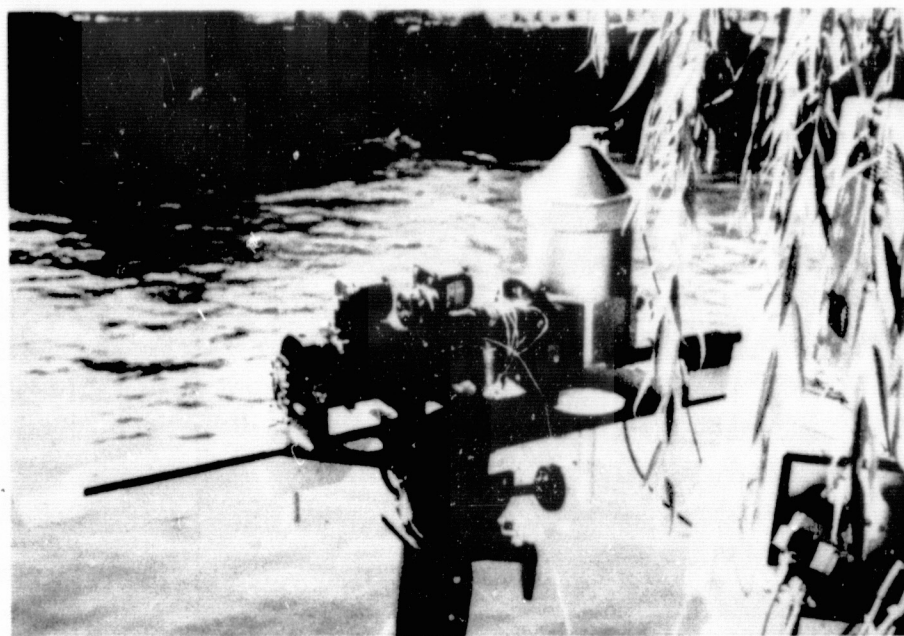


FIG. 9 CLOSE UP VIEW OF POLARIMETER WITH LHe CRYOSTAT AT THE RIGHT;
CHOPPER AND POLARIZATION ANALYZER MOTORS ARE LOCATED ON TOP
OF THE OPTICAL HOUSING

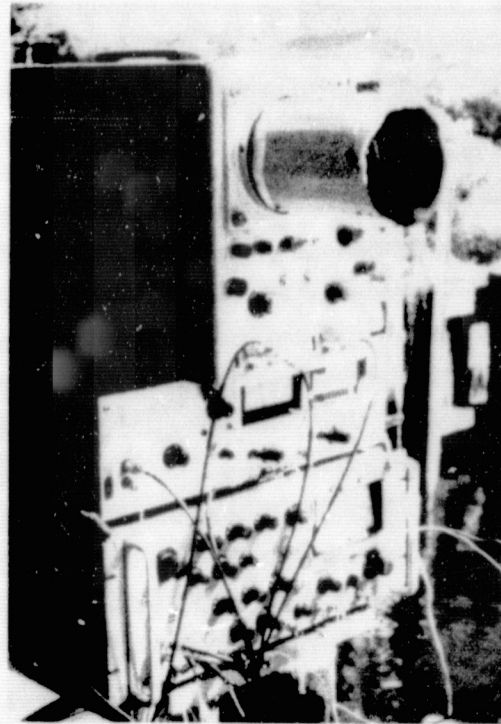


FIG. 10 ELECTRONICS ASSEMBLY: PAR 124 AT BOTTOM, PAR 129 CENTER AND OSCILLOSCOPE TOP

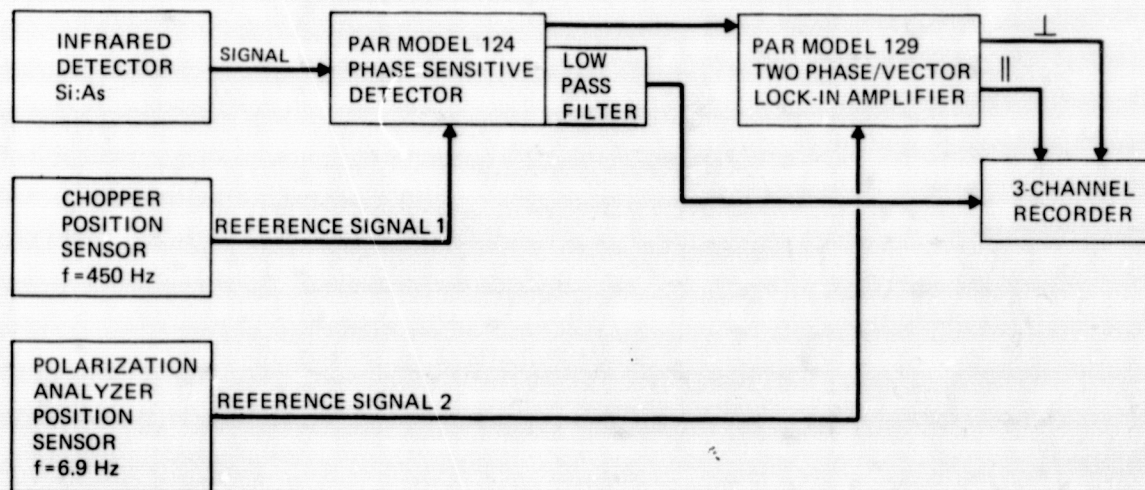


FIG. 11 INFRARED EMISSION POLARIMETER: SYSTEM ELECTRONICS

D50

N78-14514

SCATTEROMETER RESULTS FROM SHOREFAST AND FLOATING SEA ICE

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ABSTRACT

Multipolarized scatterometer sea ice measurements at 13.3 GHz obtained during the winter and spring of 1975-76 from a number of flight lines off the east coast of Canada were analysed. Radar scattering coefficients, σ° were calculated for several regions of sea ice as interpreted from aerial photographs. The variation in σ° with incidence angle is presented for HH (Horizontal transmit - Horizontal receive) and HV (Horizontal transmit - Vertical receive) polarizations for the various ice regions. The depolarization ratio ($\sigma^\circ_{HH}/\sigma^\circ_{HV}$) as a function of incidence angle is also given. The sea ice regions studied included shorefast ice with varying degrees of snow cover and surface roughness and several varieties of floating sea ice with different thicknesses.

The value of σ° for relatively thin ice can vary over a range of approximately 10 db for both the like (HH) and cross (HV) polarized signals. Further, the returns for shorefast ice show a larger variation of approximately 20 db and 25 db for the HH and HV returns respectively. These results indicate clearly the difficulty in interpreting or correlating the magnitude of the backscattering coefficient with ice type or thickness. Nevertheless, there is some indication that radars operating with incidence angles of 60° or less will acquire imagery on which the graytone will help in differentiating ice types. The scattering coefficient data also shows the contrasts between different ice regions is often a few db greater for the HV returns than for the HH returns. This was particularly true for the shorefast ice studied. A large dynamic range (30-35 db) will be required by an imaging radar operating at incidence angles between 10° and 60°

INTRODUCTION

Up to date information on the extent, position, thickness, roughness and break-up characteristics of sea ice is necessary for navigational purposes and climatological forecasting models. The need to repeatedly map large areas covered by sea ice under all weather conditions during day or night makes the use of airborne or spaceborne radar imagers particularly attractive.

The ability of radar systems to discriminate among sea ice types and their thicknesses has been studied by, amongst others, Anderson, (1966); Rouse, (1969); Johnson and Farmer, (1971); Glushkov and Komarov, (1971); Ketchum and Tooma, (1973); Parashar et al, (1974); Dunbar, (1975) and Dunbar and Weeks, (1976). Results of these studies show the need for an improved knowledge and understanding of the nature of radar returns from sea ice. For example, the values for and relative importance of various electrical (complex permittivity) and physical (salinity, temperature, surface roughness, snow cover, subsurface structure and inhomogeneities) properties affecting the radar return from sea ice are not well understood at present. Information on optimum dynamic range, sensitivity and graytone resolution are required for imaging radar design.

Understanding the effects of different radar operating parameters (frequency, polarization, incidence angle, spatial resolution) is important both for radar design and sea ice interpretation from radar images.

Some of the above information can be acquired from an analysis of scatterometer measurements. A radar scatterometer is a system designed to measure the radar backscattering coefficient σ^0 (backscatter cross section per unit illuminated area) as a function of incidence angle θ (measured from the vertical). The density or brightness displayed on a radar image produced for example by a side looking airborne radar (SLAR) depends on σ^0 . Radar scatterometers permit a more quantitative and detailed observation of radar scattering behavior than radar imagers (Moore, 1966). While an imaging radar can be made to operate with fine resolution over large areas from both spacecraft and aircraft altitudes, a scatterometer has limited ground coverage. The main objectives of conducting scatterometer measurements are to aid in the determination of parameters required for a radar imager and in developing interpretation techniques for radar imagery. The purpose of this paper is to report the results of scatterometer measurements over shorefast and floating sea ice conducted at several locations off the east coast of Canada.

SCATTEROMETER MEASUREMENTS AND GROUND TRUTH INFORMATION

Radar backscattering measurements were made with a Ryan Model 720 dual polarized scatterometer system operating at 13.3 GHz frequency. This system can transmit either horizontally or vertically polarized radiation while receiving both polarizations from an illuminated region which corresponds to $\pm 60^\circ$ along the flight line and 3° across-track. Returns from different incidence angles θ are separated on the basis of doppler shift by choosing appropriate bandpass filters. As a result, σ^0 vs time (distance) plots for each angle θ as well as σ^0 vs θ plots for individual ground resolution cells can be obtained. The original data are recorded in an analogue form and may be subsequently digitized and processed by computer.

The system was flown on a DC-3 aircraft belonging to CCRS. An RC-10 camera and a Daedalus infrared line scanner were also used during each mission; outputs from these sensors acted primarily as "ground truth" information for the scatterometer data analysis performed in this study. In-situ measurements of temperature, salinity, snow cover, and thickness of shorefast ice were also made by C-CORE and CCRS. A detailed analysis of the thermal infrared data and ground truth information has been carried out by C-CORE, (Worsfold et al, 1977).

The scatterometer data were obtained from a number of flight lines during the winter of 1975-76 off the east coast of Canada. The description of different flight lines is presented in TABLE I.

Airphoto mosaics for the flight lines were visually interpreted to delineate different areas of sea ice by considering the degree of snow cover, surface roughness, thickness, tone, texture and age. An effort was made to follow the existing WMO ice nomenclature and terminology (Dunbar, 1969) in identifying and classifying the sea ice. However, in some cases it was found difficult to specify a precise ice type or category and it was decided to use the term "region" in describing the area over which averaging of the scatterometer data was performed. The "regions" have been assigned a name and described as shown in TABLE II.

SCATTEROMETER DATA PROCESSING

The Ryan 720 scatterometer uses homodyne detection with both in-phase and quadrature channels for both the like- and cross-polarized backscattered signals. These channels are frequency offset and combined in an analogue sign sense network, called the combiner (Royer, 1975; Xhignesse, 1976) which separates fore and aft returns in the frequency domain. The aft returns occupy the frequency range below 10 KHz and the fore returns are shifted up in frequency above 10 KHz. The two output signals of the combiner correspond to the like- and cross-polarized signals and are recorded on a 3M Mincom instrumentation tape recorder.

The analogue data can be processed as such or subsequently digitized and processed by a digital computer. In the analogue processing, σ° for each incidence angle is obtained by passing the recorded signal through an appropriate bandpass filter centred around the corresponding doppler frequency. The resolution cell length is determined by the bandwidth of the filter. The width or the across-track resolution cell length for both analogue and digitally processed data is limited by the 3° antenna beamwidth and varies from 15 m. at $\theta = 0^\circ$ to about 30 m. at $\theta = 60^\circ$ for an altitude of 300 m. The analogue processing provides a quick look at the σ° time history plots and was used as such in the preliminary analysis. It also provided σ° vs θ curves for the Bay of Chaleur flight line even though averaging over regions could be done only visually.

A 12 bit digitization was performed for digital processing at a rate of 50 KHz and subsequent digital data stored on computer compatible tape. For a digitization rate of 50 KHz, the time record length T for Fourier transformation was fixed at 0.2547 seconds which corresponded to 3×2^{12} data samples. The distance VT (about 15 m. at 60 m./sec. velocity) traversed by the aircraft at velocity V was selected as the basic resolution cell length, ΔL . The $\pm 60^\circ$ instantaneous antenna footprint was divided into adjacent resolution cells of constant length ΔL . The centre angle of incidence, centre doppler frequency and doppler bandwidth for each of above resolution cells were computed by considering both velocity and altitude. The digital data processing consisted of obtaining doppler frequency spectrum of subsequent record lengths T in the flight line through fast Fourier transformation. σ° for each resolution cell was obtained by averaging the spectrum within the bandwidth centred around the corresponding central doppler frequency. σ° vs θ for each resolution cell was obtained by time shifting the results from each successive record length T as each cell was viewed at different time at each incidence angle. To reduce the number of incidence angles (which can be as many as 100 for both fore and aft), σ° in each interval of 10° (between 0° and 10° , 10° and 20° , 20° and 30° , 30° and 40° , 40° and 50° , 50° and 60°) was averaged and the mean angle was associated with the averaged σ° value. This resulted in six incidence angles with more data samples being averaged at the larger incidence angles than near nadir. The above data processing procedure utilized all of the relevant doppler frequency spectrum thereby maximizing the number of independent samples averaged in each resolution cell. The details of the data processing are given by Chan and Gray (1977).

The errors in the absolute value of σ° can be attributed mainly to an imprecise knowledge of the antenna patterns. Systematic errors of up to 2 db for the HH and approximately 3-4 db for the HV results are possible. Smaller errors (< 1 db) may also be introduced through errors in aircraft ground speed and altitude. An uncertainty in the value of σ° is also present because of the statistical nature of the returns. However, due to the averaging described above, the random errors from this source are also small (< 1 db).

SCATTEROMETER DATA ANALYSIS

The first step in the data analysis consisted of aligning σ° time history plots (σ° vs time for each angle θ) with airphoto mosaics of the corresponding flight lines. Sea ice in the different flight lines was divided into different regions as described above. Scatterometer data corresponding to individual regions were identified and σ° vs θ curves produced for each region by taking an average over the corresponding segments of ice. Only homogeneous segments of ice were considered for averaging and points near the boundaries were deleted. The aft scatterometer measurements were analysed and the results presented correspond to HH and HV polarizations. The effects of antenna pattern errors are evident in the presented σ° vs θ curves for HV polarization at high incidence angles. However, the differences between scattering coefficients for different regions are independent of possible antenna pattern errors at any incidence angle.

Results for Forteau Bay

Sea ice in this flight line consisted predominantly of different varieties of shorefast ice and rafted young ice. Radar scattering coefficient σ° as a function of incidence angle θ for the different ice regions is shown in Figure 2 for HH polarization. As expected, open water gives maximum return at near vertical incidence and decreases relatively rapidly with increasing angle. On the basis of the aerial photography, new ice could not be differentiated from open water because both gave a black tone on the air photos. However, new ice could be distinguished on the scatterometer time history plots because of a significantly lower return at near vertical incidence as compared to open water. There was some drift during this flight line and it is possible that there could be a variable mixture of open water and new ice in the footprints at different incidence angles. Unfortunately, because the regions of new ice were not visible on the photography there is some doubt about the validity of this curve for incidence angles greater than 30° . Rough first year shorefast ice gives maximum return at angles greater than 20° followed in order by medium rough and smooth first year shorefast ice regions. Rafted young ice gives almost the same value of σ° as medium rough first year shorefast ice although it is clear that the rafted ice is thinner. The large range of as much as 20 db in radar return from three shorefast regions is worth noting. It is difficult to attribute this range only to the visible changes in the surface features; the variability of snow cover and subsurface structure could also contribute to the differences in backscatter. The number of resolution cells averaged varied from a minimum of 9 for open water to a maximum of 117 for medium rough first year shorefast ice region. The standard deviation varied from less than 1 db to 2 db.

Backscattering coefficient σ° vs θ for HV polarization is shown in Figure 3 for corresponding ice regions. The order of return from various ice regions is similar to that for HH. It appears that the separation between various regions is slightly more for HV than for HH. The HV curves are flatter when compared to HH curves. Figure 4 shows depolarization ratio $(\sigma^\circ_{HH}/\sigma^\circ_{HV})$ vs θ for the same ice regions. Separation between the various regions is at maximum between 10° and 30° and decreases for the larger incidence angles.

Notre Dame Line 1

The sea ice in this flight line consisted predominantly of thin ice such as nilas and pancake ice. Figure 5 shows σ° vs θ for HH polarization corresponding to the various ice regions. Wave structure in the open water region could be seen (Figure 1a). This suggested that the water surface was rougher because of wind as compared to the smoother water surface in the Forteau Bay flight line. A comparison of the "water" curves for the two lines shows that the results for this line are approximately 5 db higher than the Forteau Bay line at the larger incidence angles, thus confirming the relative roughness of the water surface. The thicker pancake ice gives maximum return for angles away from the vertical followed by thin pancake ice and rafted nilas. It is interesting to note that in this case rafted nilas produced less backscatter than water at all incidence angles. The large range in radar return (as much as 15 db) from four thin ice regions appears to be related to surface roughness although surface temperature and salinity may be significant. The number of resolution cells averaged varied from a minimum of 41 for the thicker pancake ice to a maximum of 132 for open water. Again, the value of standard deviation varied from less than 1 db to about 3 db.

The corresponding σ° vs θ for HV polarization are shown in Figure 6. Thick pancake ice still gives maximum return at angles away from the vertical. At higher incidence angles, the separation between open water and thin pancake ice has decreased. Rafted nilas again gives the minimum return at all angles. Depolarization ratio $(\sigma^\circ_{HH}/\sigma^\circ_{HV})$ vs θ for corresponding ice regions is shown in Figure 7. The separation for these curves between the ice regions is greatest between 10° and 30° . The order of magnitude of the depolarization ratio from the four regions changes at high incidence angles, with open water now exhibiting the minimum value. Also, the separation among the other three ice regions decreases as compared to that at approximately 20° .

Notre Dame Line 2

This flight line contained two ice regions of relatively thin ice and a refrozen shorefast region. Radar scattering coefficient σ° vs θ for HH polarization is shown in Figure 8. The open water region was uniformly black on the aerial photographs and gives the maximum value of σ° at near vertical incidence and minimum value at the larger incidence angles. The maximum backscatter at incidence angles greater than 25° was obtained from shorefast ice which had been broken by wave action but had subsequently been refrozen into the shorefast ice. The large range of σ° values from the two thin ice regions again should be noted. The number of resolution cells varied from a minimum of 18 for rafted nilas to a maximum of 187 for the refrozen shorefast ice. The standard deviation varied from less than 1 db to about 2 db.

The σ° vs θ for HV polarization is shown in Figure 9. The order of return for various regions is the same as in Figure 8. The results indicate that separation among the regions is greater for HV than for HH polarization. Depolarization ratio as a function of θ is shown in Figure 10 and again, the separation among various ice regions is more between 10° and 30° decreasing at larger incidence angles.

Northumberland Strait

Curves of the backscattering coefficient σ° vs θ for HH polarization corresponding to various ice regions in this flight line are given in Figure 11. Open water in this flight line appeared black on the air photos. The rafted nilas region gives the lowest return at all angles except at the largest incidence angle where its return is comparable to that from open water. For incidence angles greater than 30° , maximum return is given by consolidated brash ice followed in order by heavily rafted nilas and rafted young ice regions. The number of resolution cells averaged varied from 5 for thin first year ice to 9 for rafted nilas. The value of standard deviation varied from less than 1 db to about 2 db.

The corresponding σ° vs θ curves for HV polarization are shown in Figure 12. The order of return from various regions remains almost the same as for HH but separation between the regions is slightly greater than that for HH. Rafted nilas now gives minimum value at all angles. Depolarization ratio vs θ for the various ice regions is shown in Figure 13 and shows a similar pattern to the other depolarization results.

Bay of Chaleur

Scatterometer data for this flight line were not digitized. Results presented in Figure 14 were obtained from analogue data by visually averaging over homogeneous regions. These are presented only to show the relative return from various ice regions. The values of σ° could be in error in respect to the digitally produced σ° vs θ plots because different averaging has been performed. Rough shorefast ice gives more return than smooth shorefast ice at all the angles for both HH and HV polarization and the difference between the two regions is significantly greater for the HV results in comparison to the HH results.

DISCUSSION AND CONCLUSIONS

A comparison of the results obtained from the different flight lines shows that the returns from similar ice regions are comparable and appear to be consistent. Differences were observed among the scattering curves obtained on the different flight lines for open water; however these undoubtedly were related to the different wind speeds, sea states and the wave damping effect of the adjacent ice cover. The effect of the ice in damping wave motion close to the ice could be seen in some of the photography for the Northumberland Strait line and also in some of the scatterometer results. The general shape of the σ° vs θ curves for the different ice regions remains similar except for the results obtained from the Northumberland Strait line which have a slightly smaller slope particularly between 15° and 45° . The reason for this is unknown. In some cases the return at 55° is greater than that obtained at 45° which probably represents a systematic error arising from imperfect antenna pattern corrections. The relatively low value for the depolarization ratio at the largest incidence angle could also be due to the antenna pattern errors.

Apart from the returns close to the vertical the highest backscatter was observed from rough shorefast ice although some smooth shorefast ice showed returns lower than those obtained from much thinner ice, e.g., pancake ice and rafted young ice. The variations in the radar backscatter from shorefast ice could be due to the nature, salinity, temperature, etc. of the snow cover as well as the nature, roughness, etc. of the ice beneath the snow. The identification and classification of sea ice types on radar imagery depends on floe size, shape, texture, location and the rafting and ridging pattern. The results presented here show that radar imagery gathered at incidence angles comparable to those used by the scatterometer will have gray scale information which will, within limits, help to identify the ice type.

The difference in scattering between the various ice regions (which is independent of possible antenna pattern errors) normally increases slightly as the incident angle changes from 5° to roughly 30° and is approximately constant for values greater than 30° . Also, the differences in scattering values or contrasts between the various ice regions at any particular angle have been observed in most cases to be slightly greater in the HV results than in the like-polarized HH results. For example, the range between the smallest and largest scattering coefficients at 45° for sea ice in the Northumberland Strait line was approximately 13 db for the HH results and approximately 17 db for the HV results. Even larger contrasts in scattering were observed over regions of shorefast ice; for example, the difference in backscatter at 45° between rough and smooth shorefast ice in the Bay of Chaleur was approximately 12 db for the HH results and approximately 18 db for the HV results. This effect is similar to changes observed by Ramseier et al (1975) and Gray et al (1977) in the backscatter from old ice and smooth first year ice at the AIDJEX site in the Beaufort Sea. The plots of the depolarization ratio also can be used to further evaluate the extent to which the HV cross-polarized results add information to that obtained from the HH results. It is evident that the maximum differences between the depolarization ratios for the different ice regions occur at approximately 10° to 25° but drop to a few db at incident angles greater than approximately 40° . Consequently, although there will be additional information in the combination of both like- and cross-polarized images in comparison to a like-polarized image alone, both will appear to be very similar. On the basis of the interpretation of dual polarized Westinghouse 35 GHz SLAR, Hengeveld (1969) observed that the detail of surface ice features appear generally sharper on the cross-polarized imagery but that new ice forms could not be identified on the cross-polarized imagery. The possibility exists that the lack of identification of the new ice forms represented simply the inadequate dynamic range of the radar, particularly (as was the case in some of this imagery) when the scene included an appreciable region of the shoreline. It is interesting to note that the angle at which the returns from open water are equal to those from individual ice regions differs for the like- and cross-polarized channel. Consequently, a high altitude airborne or spaceborne imaging radar with both like- and cross-polarized channels may differentiate regions of open water from regions of smooth ice which might otherwise not be possible with a single polarized system. It should be emphasized that our comments related to the capabilities of dual polarized radars are based on a limited data set and more research on this question is necessary.

Our data indicate that to preserve the graytone information, a large dynamic range will be required in a imaging radar in order to avoid saturation or loss of signal from smooth ice or open water. By inspection of the Forteau Bay results, a dynamic range of at least 30 db and 35 db would be required for the HH and HV channels respectively of an imaging radar operating at incidence angles somewhere between 30° and 60° . This dynamic range is probably also required for airborne radars operating at larger incidence angles.

ACKNOWLEDGEMENTS

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TABLE I. DESCRIPTION OF FLIGHT LINES

Line	Location	Date	Time (GMT)	
			From	To
Forteau Bay	Forteau Bay, Labrador	13 March 1976	16:28 : 07	16:30 : 16
Notre Dame Line 1	Notre Dame Bay	11 March 1976	16:40 : 50	16:45 : 00
Notre Dame Line 2	Notre Dame Bay	11 March 1976	17:01 : 50	17:03 : 40
Bay of Chaleur	Bay of Chaleur, (Point Caplin), New Brunswick	1 March 1976	18:10 : 00	18 : 11:00
Northumberland Strait	Northumberland Strait, Prince Edward Island	15 March 1975	14:58 : 00	14:62 : 00

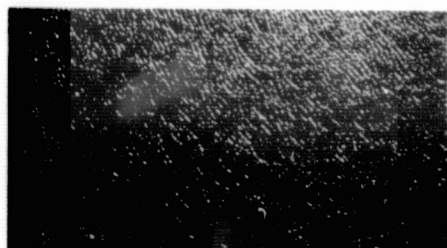
TABLE II.

- Region 1: Open Water (Figure 1a): In general, it appeared very dark on the aerial photographs. However, wave patterns were apparent under suitable illuminating geometry as shown in Figure 1a.
- Region 2: New Ice: Usually the new ice could not be distinguished from open water. When surrounded by open water, it could be identified provided that the angles of illumination and wind conditions were favourable.
- Region 3: Rafted Nilas (Figure 1b): Unrafted portions gave a dark grey tone, whereas rafted portions appeared lighter.
- Region 4: Thin Pancake Ice (Figure 1c): The pancakes were not as fully developed as in region 7. Instances of rafting were apparent, but much less prominent than in region 3.
- Region 5: Heavily Rafted Nilas (Figure 1d): This ice appeared thicker and rougher than region 3 because of much more severe and frequent rafting and ridging.
- Region 6: Rafted Young Ice (Figure 1e): Rafting occurred in large plates resulting in ice floes.
- Region 7: Thicker Pancake Ice (Figure 1f): The pancakes were well developed.
- Region 8: Consolidated Brash Ice (Figure 1g): Refrozen ice fragments in the vicinity of ice floes and in larger openings within floating ice.
- Region 9: Smooth First Year Shorefast Ice (Figure 1h): Apparently smooth ice with variable snow cover having an ice thickness of 30 to 65 cm (Worsfold et al, 1977).
- Region 10: Medium Rough First Year Shorefast Ice (Figure 1i): Similar to region 9, but with pressure ridges, less snow cover, and a smaller thickness.
- Region 11: Rough First Year Shorefast Ice (Figure 1j): Similar to region 9 but with blocks of ice protruding above the level ice.

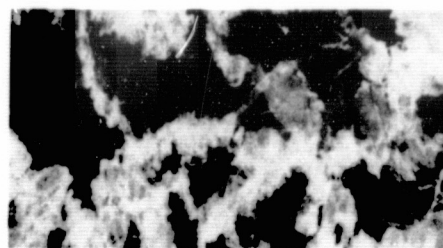
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Region 12: Refrozen Shorefast Ice (Figure 1k): Large fragments of ice broken by wave action but now frozen together and again forming part of the shorefast ice.

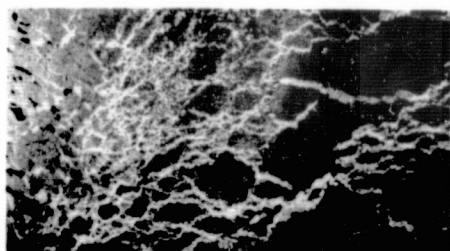
Region 13: Thin First Year Ice: An isolated ice floe visually similar to region 10.



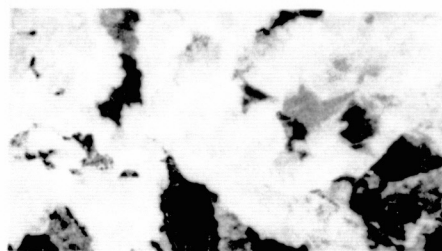
(a) Region 1



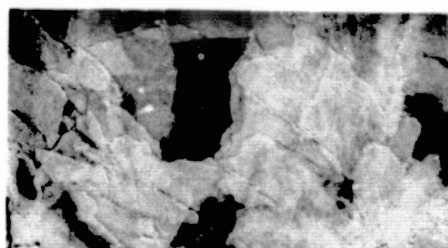
(b) Region 3



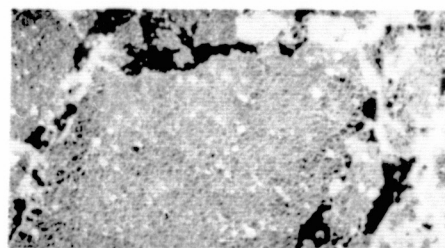
(c) Region 4



(d) Region 5



(e) Region 6



(f) Region 7



(g) Region 8

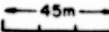
Scale  45m

Figure 1. (continued on next page) Examples of aerial photograph of sea ice for various regions.

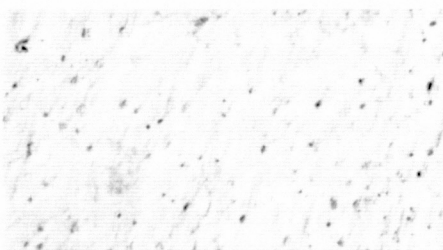
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(h) Region 9



(i) Region 10



(j) Region 11



(k) Region 12

Figure 1. (contd)

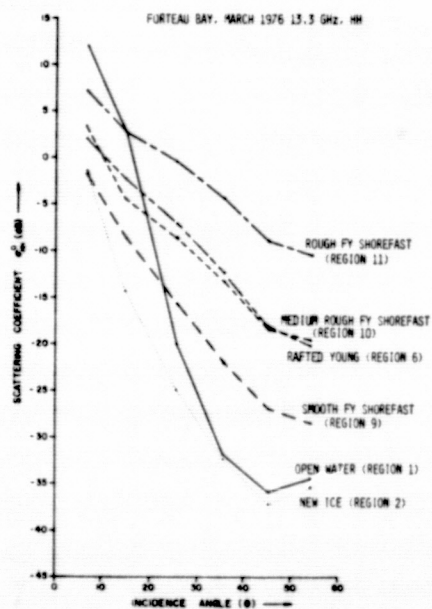


FIGURE 2. SCATTERING COEFFICIENT σ^0 vs ANGLE θ , FORTEAU BAY, 13.3 GHz, HH

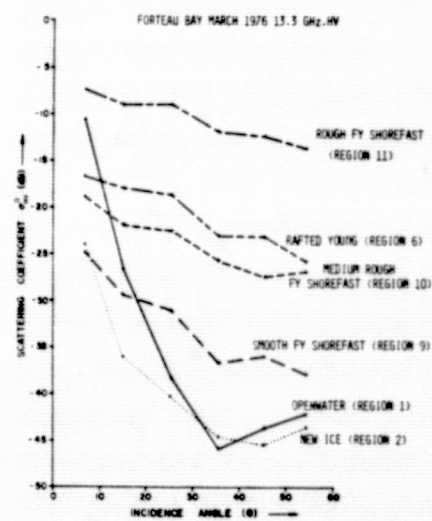


FIGURE 3. SCATTERING COEFFICIENT σ^0 vs ANGLE θ , FORTEAU BAY, 13.3 GHz, HV

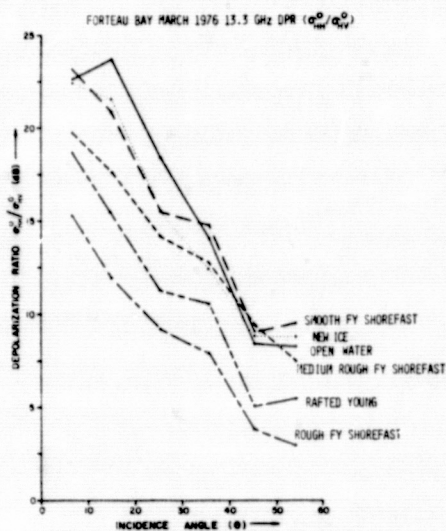


FIGURE 4. DEPOLARIZATION RATIO $\sigma_{\text{H}}^0/\sigma_{\text{V}}^0$ vs ANGLE θ , FORTEAU BAY 13.3 GHz

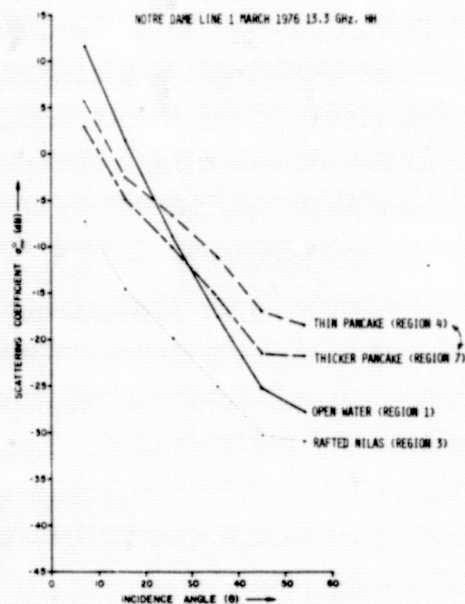


FIGURE 5. SCATTERING COEFFICIENT σ_{H}^0 vs ANGLE θ , NOTRE DAME LINE 1, 13.3 GHz, HH

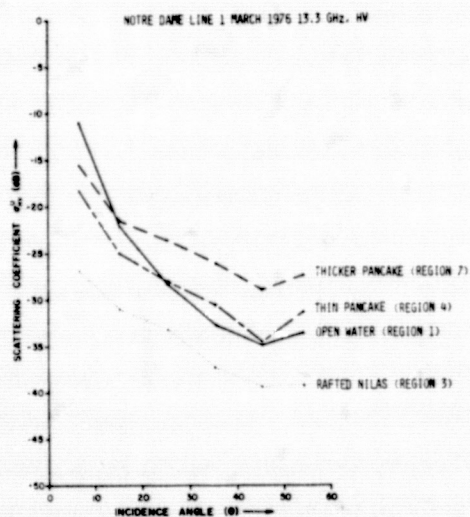


FIGURE 6. SCATTERING COEFFICIENT σ_{H}^0 vs ANGLE θ , NOTRE DAME LINE 1, 13.3 GHz, HV

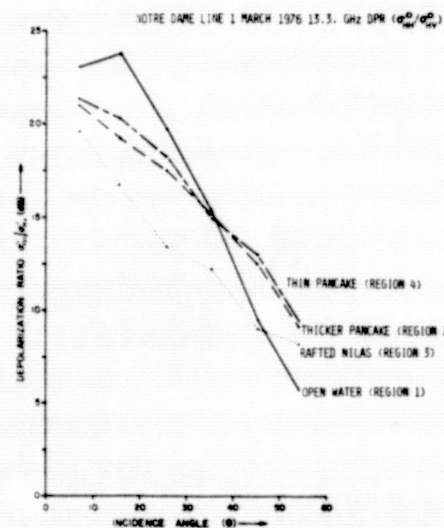


FIGURE 7. DEPOLARIZATION RATIO $\sigma_{\text{H}}^0/\sigma_{\text{V}}^0$ vs ANGLE θ , NOTRE DAME LINE 1, 13.3 GHz

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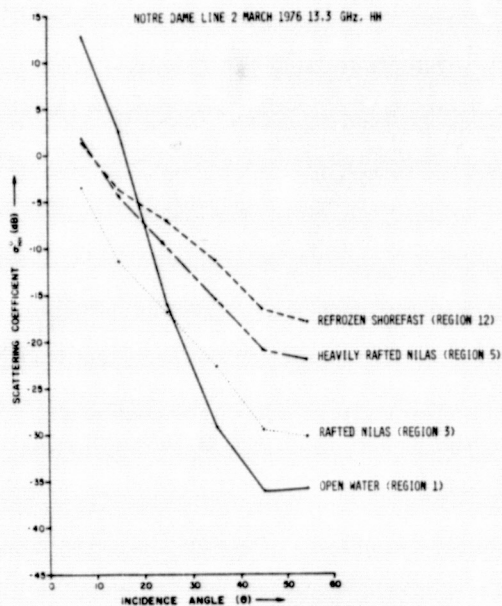


FIGURE 8. SCATTERING COEFFICIENT σ_0^{HH} vs ANGLE θ , NOTRE DAME LINE 2, 13.3 GHz, HH

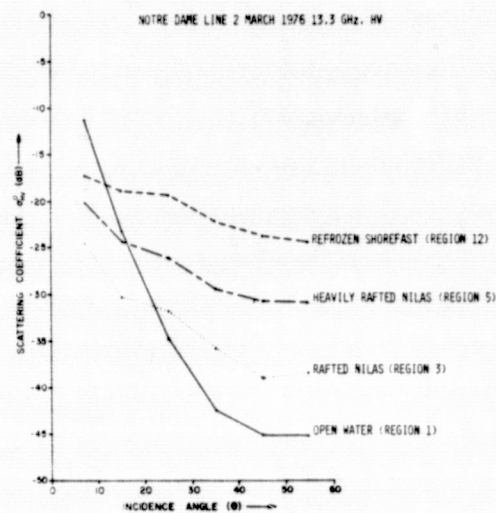


FIGURE 9. SCATTERING COEFFICIENT σ_0^{HV} vs ANGLE θ , NOTRE DAME LINE 2, 13.3 GHz, HV

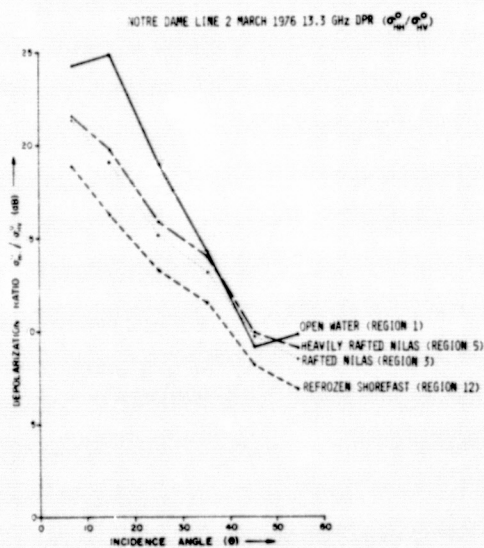


FIGURE 10. DEPOLARIZATION RATIO $\sigma_0^{HH} / \sigma_0^{HV}$ vs ANGLE θ , NOTRE DAME LINE 2, 13.3 GHz

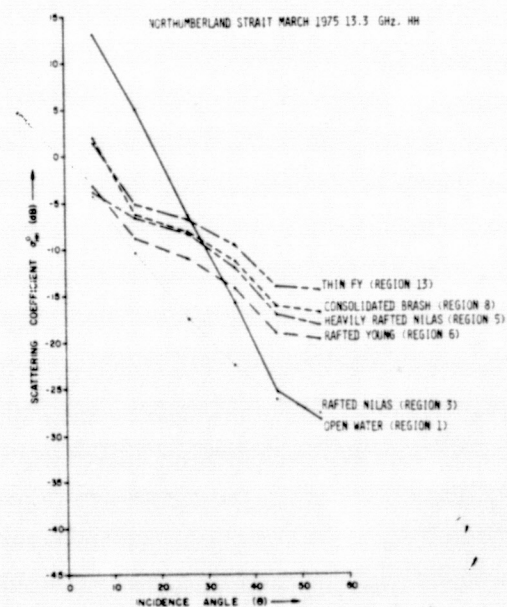


FIGURE 11. SCATTERING COEFFICIENT σ_0^{HH} vs ANGLE θ , NORTHUMBERLAND STRAIT, 13.3 GHz, HH

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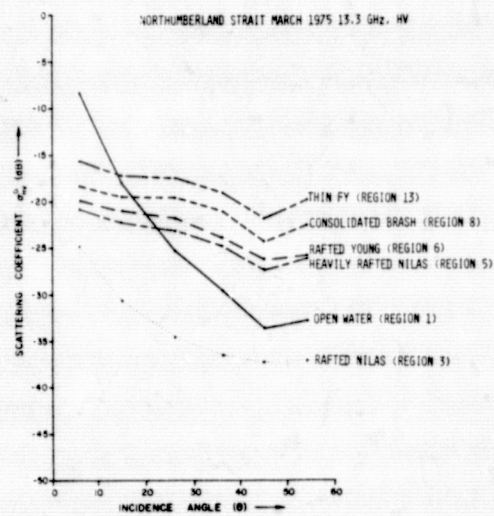


FIGURE 12. SCATTERING COEFFICIENT σ^0 vs ANGLE θ , NORTHUMBERLAND STRAIT, 13.3 GHz, HV

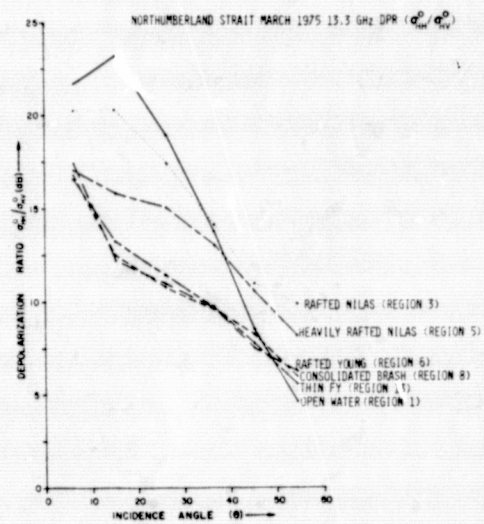


FIGURE 13. DEPOLARIZATION RATIO $\sigma^0_{HH}/\sigma^0_{VV}$ vs ANGLE θ , NORTHUMBERLAND STRAIT 13.3 GHz

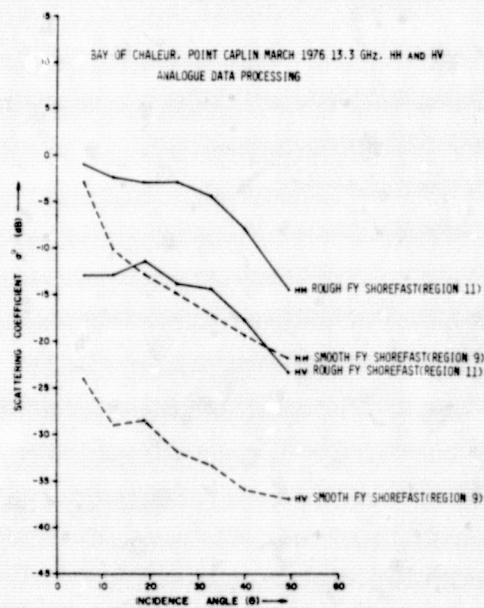


FIGURE 14. SCATTERING COEFFICIENT σ^0 vs ANGLE θ , BAY OF CHALEUR, 13.3 GHz, HH AND HV

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AN OPERATIONAL, MULTISTATE, EARTH OBSERVATION DATA
MANAGEMENT SYSTEM

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ABSTRACT

The purpose of this paper is to investigate a group of potential users of satellite remotely sensed data -- state, local, and regional agencies involved in natural resources management. We assess this group's needs in five states and outline alternative data management systems to serve some of those needs. We conclude that an operational Earth Observation Data Management System (EODMS) will be of most use to these user agencies if it provides a full range of information services -- from raw data acquisition to interpretation and dissemination of final information products.

1. INTRODUCTION AND SUMMARY OF RESULTS

This paper reports a two and one half-year investigation of Earth Observation Data Management Systems (EODMS) to meet information needs of state, regional, and local agency users in a five state midwestern region: Illinois, Iowa, Minnesota, Missouri, and Wisconsin.

The major contributions of this work are: i) a comprehensive data needs analysis of state and local users; ii) the design of priority information products that serve state and local data needs and are derivable using remote sensing; iii) analyses of the costs, performance, and data management aspects of alternative processing centers to produce the priority products; iv) the examination of pertinent policy issues in the development of Earth Observation Data Management systems; v) the elaboration of alternative institutional arrangements for operational Earth Observation Data Management Systems.

We arrive at conclusions and recommendations which differ substantially from common thinking about serving state-level users of remotely sensed data. We conclude that an operational EODMS will be of most use to state, regional, and local agencies if it provides a full range of information services from data acquisition and preprocessing to interpretation and dissemination of final information products. There is a wide gap between the digital format in which raw, satellite-derived information is presently produced by the federal government, and the tabular and map formats in which natural resources information is currently of most use to states. An EODMS which stops short of completely filling this gap will be of lesser utility than a comprehensive system. Motivated by this fact, we analyze twenty-seven broadly useful "priority" information products which an EODMS might produce from remotely sensed data.

We also recommend that EODMS provide not only satellite-derived information but also a wide variety of natural resources information obtained from

satellite, aircraft, and ground survey missions as well as a limited amount of socioeconomic information necessary to produce land use and related products. Most of the information needs we identified appear to require multiple data sources. In evaluating the capability of satellite data to serve state needs, we found that the proposed LANDSAT Follow-on mission promises significant improvement of this capability as compared to LANDSATs 1, 2, and C.

We believe that planning and management of an EODMS system should be a joint state and federal responsibility, structured institutionally in one of two ways. The system might be most responsive to the full range of user needs and might operate most efficiently if a new federal natural resources information agency were established to manage it. However, if creating a new agency appears infeasible, a system which evolves from cooperative efforts among existing institutions such as NASA, USDA, and the Department of the Interior, should receive careful consideration.

In considering how an EODMS might be structured, we find most attractive a regionally-centered system with multidisciplinary processing centers serving reasonable balance between economies from shared resources on the one hand, and accountability to users, familiarity with the local area, and product accuracy on the other.

These conclusions on system management and structure result from our analysis of four hypothetical EODMS operational systems alternatives according to criteria including system capacity and economics, responsiveness, flexibility, ease of implementation and interfacing, and impacts. The four include two similar to those mentioned above as well as a system under private sector control and another publically-controlled system.

We have analyzed the costs and performance of systems to produce priority products for the five states. We estimate that a multidisciplinary, satellite-based processing center could produce the twenty-seven priority information products for the five state region at yearly cost of about \$13M--including all system overhead. Less than 15% of this cost is associated with satellite data acquisition and computer processing, while much of the remainder is due to aircraft and ground survey data gathering and processing. This fact implies that improving sensor performance to reduce ground truth requirements might have a more profound effect on reducing total system costs than would development of more efficient computer processing techniques.

We also compare the cost-effectiveness of producing the priority products for the five states using computer processing of satellite data of LANDSAT Follow-on specifications with traditional processing of aircraft data. The satellite-based techniques cut costs by about a factor of four and reduce the time required by 50 to 75% while retaining sufficient geometric accuracy to meet user requirements. However, the price paid for these improvements might be a loss of a few percentage points in classification accuracy.

We investigated economies due to resource sharing resulting from centralized processing in a multistate, multidisciplinary center. Sharing resources among disciplines seems, by one measure of comparison, to save about 25%. Centralizing processing geographically also results in savings; five state centers appear to cost forty-five percent more than one regional center serving our area. However, centralizing to one national facility apparently saves at most another five or ten percent while risking loss of contact with users.

The methodology and focus of this study set it apart from other data needs analyses and system design studies. This study is one of the few data needs analyses for remote sensing whose primary concern is potential users in state, regional and local government. Of the few needs analyses done for this group, this is the only one whose final goal is to outline and assess system alternatives to serve these users.

As a system design study, a distinctive feature of this project is our careful adherence to a real-world, rather than theoretical, context throughout. The products our systems are designed to produce can serve real needs, which exist today in day-to-day activities in the agencies. Furthermore, our

proposed system management structures take into account current state and federal institutions, together with their governing laws and regulations. Finally, we have addressed a broader range of potentially controversial policy issues in order to highlight questions which system designs ought to address.

2. STATE DATA NEEDS AND PRIORITY PRODUCTS

2.1 DATA NEEDS SURVEY METHOD AND PHILOSOPHY

As a prelude to conceptualizing alternative EODMS systems, we developed a data base of information on current agency operations. We gathered information on the tasks agencies perform, the roles of these tasks in decision-making, the frequency with which tasks are performed, and the priorities among tasks. We identified those data used in performing specific tasks, their characteristics, how they were processed and from what sources they were derived. Our data base includes only data items actually used or required to meet current responsibilities. The EODMS team worked closely with agencies responsible for the management and development of renewable and nonrenewable resources, for transportation planning and development, for state and regional planning and for environmental protection. We organized activities of agencies into categories of task and subtask wherever possible.

For each task, we sought a detailed set of information including: its priority, its frequency of occurrence, the agency initiating it, the reason for initiating it, the agency that performs it, and extensive information on how and with what data the task was performed. Under this latter heading, we listed the data types used, their sources and format, and the processing methods applied. We also noted time constraints, final products produced and how they were disseminated, and the accuracy achieved. In addition to describing each task in this manner, we investigated the role of the task outputs in decision making, noting final users, decisions to be made, and accuracy and timeliness required for decisions.

The major difficulties encountered in assessing the tasks and data needs of agencies were in specifying acceptable delay times between requests for data and their receipt and data accuracies required. These are important considerations in designing data management systems. Thus, when agency representatives could not provide the detailed responses sought, we developed our own estimates based on our understanding of their needs.

Although we studied the data needs of agencies in all five states of the study region we investigated, Missouri agencies were studied in greatest detail. Early in 1975, the Missouri Inter-Departmental Council on Natural Resources Information facilitated our work by encouraging agency cooperation and by identifying and introducing us to agency representatives. This cooperative effort with Missouri agencies culminated in the preparation of an EODMS project report, Natural Resources Data Requirements Inventory: Missouri (1), which we completed in October, 1975. That report represents the most comprehensive data base developed for any of the five states in the study region. We subsequently used it as a point of departure for discussion with some agencies in the other four states.

2.2 PRIORITY INFORMATION PRODUCTS

From the data base of user needs, we formulated a set of priority information products an EODMS could produce. Multiple factors shaped our thinking as we moved from a data base of hundreds of fundamental data needs and currently used information products to a specification of twenty-seven priority products. We were concerned that the products have multiple uses by many agencies to insure significant demand or be central to the operations of at least one agency, that the number of products not be excessive, yet represent a sufficient variety of technical characteristics to provide a realistic set of production requirements for EODMS system design studies, and that they be based on a significant input of satellite gathered data.

We formulated a set of priority product candidates by screening the data base of user needs for data items which feasibly could be acquired by remote sensing systems. We aggregated the screened data needs by application areas to highlight their commonalities and differences. From this aggregated

list of seventy-eight data items we postulated and quantitatively described a set of priority products. Critique by our state agency partners then completed the development of the list of twenty-seven products which we ultimately used in EODMS system design considerations.

The products are: Forest Management Map, Agricultural Management Map, Level I Land Use Maps, Level II Land Use Maps (small and large scale for rural and urban areas, respectively), Vegetative Cover Type Map, Soil Map, Forest Stand Maps, Timber Volume Estimate Table, Fire Measurement Maps, Water Impoundment Volume Maps, Lake Trophic Status Map, Recreation Map, Industrial Map, Topographic Map, Slope Maps, Orthophotoquads, Geologic Maps (rock type), Structural Geology Map, Surficial Materials Map, Construction Materials Availability, Flood Prone Areas Map, Flood Inundation Area Map, Earthen Dam Condition Map, Drainage Basin Maps, Sinkhole Location Maps, and Basic Imagery.

As a final step, we characterized each product quantitatively as shown in Table 1 to specify the amount and quality of the products our hypothetical system designs would have to produce.

3. REGIONAL PROCESSING CENTERS TO PRODUCE THE PRIORITY PRODUCTS: COSTS AND PERFORMANCE

This section deals quantitatively with design issues for systems that produce the priority products. We estimate costs and performance of two alternative designs for a regional processing center to produce these information products for the five states. One of the two designs employs computer processing of satellite data, while the other uses only traditional photointerpretation of aircraft data.

3.1 COST AND PERFORMANCE ESTIMATES: GOALS AND METHODS

Performance measures of interest are classification accuracy and the age of information when it reaches the user. In addition we estimate costs excluding development charges but including capital costs (equipment and buildings) as well as operating costs (satellite, aircraft, and ground data gathering, automated and manual interpretation, cartography, printing, etc.). With these cost/performance estimates as a basis, we assess cost effectiveness of satellite-based processing (by comparing the costs and performance of the satellite- and aircraft-based systems) and the cost savings possible with resource sharing.

We base our cost and performance estimates on observed data where possible. For example, we use documented USGS experience (2) to estimate costs of producing land use maps by photointerpretive techniques. Where these data are available and applicable, we extrapolate them to fit the conditions that would exist in a five-state production center.

Extrapolation fails, however, in two situations: first, when production cost and performance data are not available for many of the priority products (some have never been produced); and second, when the change from a small, experimental to a large, operational system changes production methods. An example of the latter situation occurs when the change requires that a faster computer system be used to process the increased data load.

To analyze products for which no data were available, we broke their production down into steps on which we have cost and performance data from other products. As an illustration, the satellite data processing and multi-stage sampling steps involved in timber volume inventory (on which we have detailed data) correspond to those that might be used in lake trophic status mapping (on which our information is scanty). References (3, 4) provide more details.

To estimate costs of large computer processing systems, we developed a theoretical method for analyzing computer processing times and costs for information products based on digital, remotely sensed data (3, 5). The method determines processing times and costs as functions of image data parameters (number of pixels and bands per pixel) and processing variables (number of

classification classes and iterations required to achieve acceptable classification accuracy).

As one example of our cost analysis, we briefly review some elements of the computer system costing. The amount of digital data processing required to produce the priority products from satellite data determines the computer system size and cost. We assume that only satellite-derived data are digitally processed; that is, that supporting aircraft and ground survey information do not significantly increase the digital processing load. We also assume that data of LANDSAT Follow-on specifications are used. Finally we exploit all possible overlaps in processing among the satellite-based products.

We sought a subset of the menu of priority products which contained all the satellite-derived information displayed in the priority products, so that the other products can be derived from these "fundamental" ones without further processing of raw satellite data. Thus specifying a list of "fundamental" products reduces the center's processing task to a minimum.

We have found (3) that four "fundamental" products display all classes in sufficient detail and with sufficient coverage so that all of the other priority products can derive their satellite-based information from these four. These products are: 1) Level II Land Use maps; 2) Vegetative Cover Maps; 3) Timber Density Maps (a satellite-derivable input to the Timber Volume Estimate Table); 4) Lake Trophic Status Maps.

The yearly processing load (that is, the number of images to be classified and the number of classes into which each image must be classified), is determined solely by the four "fundamental" products. Four characteristics of each product determine processing requirements: 1) the number and type of classes it displays; 2) the area it covers; 3) its update frequency; 4) the seasonal schedule of its imagery acquisition.

Reference (3) uses these characteristics to calculate the yearly center processing load, which is as follows: 1. Preprocessing: reformat 99 images in seven bands, geometrically correct 99 images in four bands, and overlay bands equivalent to LANDSAT 1 and 2's bands 5 and 7 for 45 pairs of images. 2. Cluster analyze selected portions of equivalent of four bands of 64 images. 3. Classify (by maximum likelihood) data for the four fundamental products as follows:

- | | |
|----------------------------|--|
| a. Land-II Land Use | 10% of 9 images into 16 classes (4 iterations) |
| b. Vegetative Cover Map | 100% of 45 images into 17 classes (4 iterations) |
| c. Timber volume Inventory | 31% of 9 images into 5 classes (2 iterations) |
| d. Lake Trophic Status | 0.5% of 45 images into 5 classes (2 iterations) |

4. Carry out various overhead and input/output operations.

Using our method for calculating computer processing costs and times, we determined that a CDC 7600 would be 80 to 90% utilized in accomplishing the above workload on LANDSAT Follow-on imagery. This choice of computer system determines a number of center operating costs: computer mainframe and peripheral devices, computer programmers and operators, and a share of building and maintenance costs.

We also estimated other costs for the aircraft- and satellite-based centers. We planned and costed aircraft and ground data gathering missions (again taking advantage of overlaps among products), photointerpretation, cartography, and so on. We also estimated capital costs. Table 2 presents the satellite center results (3). In this table, buildings are amortized over twenty years at 10%, and equipment over five years at 10% for a system lifetime of twenty years. Computer equipment is assumed to be leased.

3.2 DISCUSSION OF RESULTS

In general, we have found that both aircraft-based sensing methods and satellite data processing can be expensive, but multidisciplinary processing for resource sharing can significantly reduce costs. A centralized, efficiently designed, satellite-based system appears to be a cost effective way of

producing the "priority" information products. More specific results of our work are described in the text to follow.

3.2.1 UTILITY OF SATELLITE DATA. Many of the priority information products can be assembled from LANDSAT data with current or "Follow-on" specifications. Of the twenty-seven priority products, (a) 67% can employ satellite data of 30 m resolution or coarser as a useful input. (b) All of the 24 map products are useful at a scale of 1:24,000 or smaller, implying a needed geometric accuracy of ± 12.7 m or 4/10 of a 30 m LANDSAT Follow-on pixel, a fractional pixel accuracy right at the current state of the art of geometric correction systems. (c) 89% can be used when updated annually or less frequently, allowing sufficient time for all computer classification, ground truthing, photointerpretation, compilation, and computer-aided printing.

3.2.2 DATA PROCESSING SYSTEM CONSIDERATIONS. We believe that raw satellite imagery or satellite data classified into 41 ground cover classes provides all needed satellite input to priority product production. In almost any geographic region, prior classification into seven aggregate classes reduces the number of classes to be extracted in an area to 10. All but one of the satellite-based priority products can apparently be derived from the following seven aggregates of the 41 "basic" ground cover classes: Urban/Industrial (9 classes), Agricultural (6 classes), Forested (5 tree type classes and 5 density classes), Other Natural Vegetation (5 classes), Water (7 classes), Non Vegetated, Non Urban (3 classes) and Other (1 class). A priori knowledge of ground truth often permits separating an imaged area into regions based on seven aggregate classes. The maximum number of classes which must be extracted from any such region is ten, including one "other" class. The priority products in final form are based on further refinements of the satellite-derived classes, which must be done manually using aircraft data and ground survey information.

Processing the required yearly satellite data load for the priority products for the five states is well within the capability of current, commercially available third-generation computers. About fifty-four equivalent satellite images per year must be corrected and classified into one or another subset of the 41 basic classes to produce the priority products for the five-state region. With Follow-on imagery this implies a throughput of 82% utilization of a CDC 7600.

3.2.3 COST EFFECTIVENESS OF SATELLITE-BASED PRODUCTION TECHNIQUES. If LANDSAT Follow-on data are used, satellite-based production of the priority products is cost effective, as compared with aircraft techniques. The \$13M satellite center cost (see Table 2) compares to a \$48M estimate for an aircraft-based center (3), while equivalent accuracy and improved timeliness can probably be achieved using LANDSAT Follow-on data.

We estimate that within an operational center (with its normal waits for service) the information on the priority products for the five states produced by a photointerpretation-based system would be 21 months old, on the average, when it arrives at user agencies. This compares with an estimated average age of 10 months in the satellite-based system, a 52% improvement. In addition, a limited body of information leads us to expect that accuracies of both location and classification for the satellite-based system will approach those of an aircraft-based system, assuming LANDSAT Follow-on data are used. Finally, the most intensive possible use of satellite data and computer classification in a multidisciplinary regional processing center cuts cost by about 70% over a system which does not use these techniques, for an area modeled on the five state region. The \$13M and \$48M estimate includes all computer costs, operator charges, aircraft and ground truth missions, photointerpretation, compilation, cartography, and amortized capital costs for buildings and equipment. These estimates may be in error by 20% or more, but we believe that their relative magnitudes are correct, since the same assumptions were used in deriving both figures.

3.2.4 ECONOMIES DUE TO RESOURCE SHARING. In the five-state region, centralizing processing from five state centers to one multistate facility results in significant cost savings. We estimate a total cost savings of 45%. Further centralization in one national facility may reduce total costs by only another

five to ten percent, however. This savings may be offset by reduced user access and by some loss in interpretation accuracy due to lack of familiarity with local conditions.

4. ALTERNATIVE INSTITUTIONAL STRUCTURES FOR EODMS

4.1 CRITERIA FOR EVALUATING ALTERNATIVES AND SUMMARY OF RESULTS

Four major institutional alternatives for EODMS were constructed by making choices among the following key system characteristics: 1) the scope or nature of the system data; 2) the character of the centers where the crucial function of interpretation is performed; 3) the distribution of functions among the national, state, and regional levels; and 4) the institutional mechanism under which the overall system operates. The four system alternatives are:

- System A: An Evolutionary System Based Upon Present Institutions
- System B: A Natural Resources Information System With Interpretation At A National Center
- System C: A National Data System With Interpretation at Regional Centers
- System D: A System Under Private-Sector Control.

These alternatives were evaluated according to a set of criteria: 1) Capacity and Economics. Is the system likely to have the capacity to produce all the priority products with the required timeliness and accuracy? What are the economies of diseconomies to be expected from each system? 2) Responsiveness and Flexibility. Will the system be sufficiently responsive to users? Can users whose data needs are not initially well defined be satisfied? Can all information present in the system be speedily accessed when necessary? Can the system satisfy new users as well as established users? Will the system be sufficiently flexible to: provide special products to meet one time or irregular data needs; accommodate improvements in the technology of remote sensing, data processing hardware and software; adapt to changing needs for information; and evolve towards production of more specialized information products as use increases? 3) Interfacing. Will the EODMS data base be able to interface readily with external systems? Can existing information systems of participating agencies be incorporated in the system? Will the system provide output in formats desired by users? 4) Implementation and Impacts. What are the obstacles to implementing each model? Will there be large front-end capital costs? Will agencies resist having some of their functions pre-empted? Will they resist assuming additional functions or reorganizing? Will there be problems getting sufficient funding for the system to plan its evolution in an orderly way? Are legal challenges likely? Is a phased implementation more likely to succeed than one involving major change? Can a go-ahead decision be made before potential users commit themselves to full participation? What are the economic, social and political impacts to be anticipated for each alternative?

The four alternatives, along with their principal characteristics and our evaluation based upon the aforementioned criteria are summarized in Table 3. The evaluation is subject to several assumptions and constraints described in (3). In particular, we have required that the system deliver a broad spectrum of interpreted information products to state, local and regional public sector users.

4.2 MOST ATTRACTIVE SYSTEM ALTERNATIVES FOR FUTURE DETAILED SYNTHESIS, DESIGN, AND ASSESSMENT

Based upon our analysis of the four system alternatives, we conclude that two public system concepts seem promising for future study. The first is a modified System A, an evolutionary system based on present institutions in which an interagency council involving NASA, USGS, USDA and other federal agencies pools their resources to delivery priority information products with a minimum of duplication to state, local and regional users. Although the structure of such a system would seem to favor what we have described as "disciplinary" (i.e. existing mission-oriented agency) approaches, we believe it important that ways be found to involve more than one agency in the operation of processing centers. We also believe that a substantial amount of activity should be carried out at the regional or large-state level.

The second promising alternative, a hybrid of System B and C, involves the creation of a natural resources information system with processing at regional and large-state multidisciplinary centers. In several respects, this alternative appears the most attractive to us. However, it requires the creation of a new government agency, perhaps within an existing department, for implementation. We believe that such a step may yield substantial benefits and should receive serious consideration.

We do not believe that a system under private sector control, System D, is likely to be an appropriate mechanism for providing the services to state, local, and regional agencies which have been the central focus of our study. However, we do believe that many opportunities for private sector business will be created by developing the kind of public sector system we envision.

5. POLICY ISSUES IN SYSTEM DEVELOPMENT

5.1 OVERVIEW

The development of an operational EODMS is contingent upon resolution of a complex set of policy issues, which can only be outlined briefly in this paper. Policy issues are those questions which arise that must be decided in the political process; while analysis may serve to illuminate the consequences of each decision, the issues themselves must be decided among contending parties. The resolution of these policy issues will serve in large measure to determine the nature of EODMS as, and if, it develops.

A number of the issues which arise require resolution by the Congress and the President through law making and the budget process. In our view a framework does not now exist within government to implement EODMS through administrative decision alone, whether made by a single agency such as NASA, USDA, or DOI, or through an interagency agreement among several agencies. This view is supported by two points. First, Congress and the President approve the funds for R&D for each satellite system as line items in the budget. Second, the kinds of systems typified by EODMS require a number of agencies to adapt and cooperate at a level that no interagency working group is likely to achieve. This is especially true in view of the fact that EODMS would replace as well as augment existing agency programs for mapping and information provision. The most likely outcome of a failure to act on the part of Congress and the President is a de facto decision not to implement EODMS.

In the remainder of this section we discuss selected issues which have arisen through our study of alternative systems.

5.2 SELECTED POLICY ISSUES: A COMMENTARY

Should EODMS be developed? The EODMS study team takes no position on this question. At minimum any kind of system requires a Congressional and Presidential commitment to continued services now provided by NASA and the USGS EROS Data Center, including continued provision of current resolution MSS data through satellites beyond LANDSAT I and II. To implement a full range of services requires coordinated decision making by federal, state, regional, and local agencies which would include anticipatory and participatory planning by all parties at interest. One strong argument in favor of EODMS is that state and local agencies face a growing range of federal mandates to gather and use natural resources and related data without sufficient additional funding. A strong federal data system could help to provide the necessary data. Cost/benefit analysis will be of limited use in making the decision regarding implementation.

What roles should be played by the private sector in EODMS? We describe four systems which range from nearly completely public to nearly completely private in ownership, management, and operation. We are highly skeptical of the potential of private sector systems to meet the data needs of state and local agencies due to difficulties in market aggregation and the limited resources of individual government units. Furthermore, serious political questions can be raised regarding the propriety of restricting, by price, free public access to data gathered by publicly owned satellite systems. Conversely, the private sector may be able to respond more readily to specific needs of user agencies or private users.

What roles are to be played by various agencies at various levels of government? For a system to be responsive to state and local needs, it must include participation by users at all levels and in all affected agencies. At the same time, state and local governments have neither the technical nor financial resources to own and operate their own systems, so a heavy federal presence is necessary. We outline in the previous section alternative ways in which various agencies and levels might work together. It is especially important that a federal focus of responsibility for EODMS be identified in the planning stage.

Who will pay, and how much, for EODMS products? The Freedom of Information Act appears to limit charges for EODMS products to reproduction and handling charges. Yet someone must pay for the initial data acquisition and product production. Thus, either a federal operating subsidy or a special act to establish some version of full cost recovery charges will be required.

What range of information products, technical assistance, and services will a system provide? We envision EODMS producing final information products in user format on a regular basis, as well as raw imagery and special interpretive services. Others see EODMS providing only imagery, or, at the other extreme, providing resource management modeling services or, ultimately, decisions. Beyond these broad issues lie questions regarding which inputs to employ, products to produce, formats, scales, accuracy, timeliness, and so on. Each of these issues strikes at existing interests as well as system costs.

What will be the relationship of EODMS to other countries? Current U.S. policy is open access to all imagery by anyone collected anywhere. This policy is not universally accepted, and it may not be adequate if higher resolution, permanent systems are installed. Furthermore, access to imagery is not equivalent to effective access for countries with limited technical capability. Finally, reasonable policies for cooperative management and cost sharing will be needed.

What unintended side effects may follow from EODMS and how can they be managed? EODMS would affect a myriad existing relationships within government, and the rest of society. For example, it could lead to further centralization and professionalization of state and local government, further removing the processes of government from effective access by ordinary citizens and small business. Some persons have expressed concern that EODMS may represent a further threat to personal privacy; frequent surveillance from space may lead to further erosion of the "right to be let alone." These are only two impacts among many identified in our study; to date, policy makers have not focused on such questions. Indeed, many such impacts may be unavoidable if EODMS is put in place.

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ACKNOWLEDGEMENT

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TABLE I. PRODUCT CHARACTERISTICS FOR FOUR SELECTED PRIORITY PRODUCTS

Product	Product Scale	Area Covered by One Product	Area Over Which Product Required in Five States	Categories Per Product/ Relevant Categories Derivable From Satellite Data	Product Update Frequency
Level II Land Use Map A	1:250,000	19,490 km ²	entire area 835,530 km ²	28/28	5 years
Level II Land Use Map B	1:24,000	155 km ²	urban areas (<5% of total)	16/16	5 years
Vegetative Cover Type Map	1:24,000 1:250,000	155 km ² 19,490 km ²	vegetative, non-urban areas (85% of total)	20-30/15	annual
Soil Map	1:24,000	155 km ²	selected areas	30/15	20 years
Timber Volume Estimate Table	---	one forest (varies)	forested areas (31% of total)	5/5 (density)	5 years

TABLE II. COSTS OF THE SATELLITE BASED CENTER SERVING THE FIVE-STATES

1. Fixed Costs

	Total Costs	Annual Costs
Capital Costs		
Buildings: 8100 ft ² @ \$70/ft ²	5,670,000	
Landscape and Parking = 8% Bldg	450,000	
TOTAL BLDGS	6,120,000	
Equipment		
Office and Administrative	184,000	
Photo Interpretation (\$150K, each PI)	8,250,000	
Cartographic (\$100K, each cartographer)	1,000,000	
Reproduction and Primary Print Equipment	100,000	
Photo Processing	100,000	
Miscellaneous	115,000	
TOTAL EQUIPMENT	9,750,000	2,250,000
TOTAL INITIAL CAPITAL INVESTMENT	15,900,000	
TOTAL FIXED COSTS		3,240,000

TABLE II. COSTS OF THE SATELLITE BASED CENTER (continued)

2. <u>Operating Expense</u>	<u>Annual Costs</u>
<u>Computing Facilities</u>	
CDC 7600 yearly lease cost	\$ 532,000
I/O devices & bulk memory	763,000
<u>Data Acquisition</u>	
(Satellite and Aircraft)	1,150,000
<u>Personnel</u>	
55 photointerpreters @ \$18K/ annum.	990,000
10 photointerpreters @ \$15k/ annum.	150,000
20 computer programmer/ analyst @ \$18K	360,000
70 ground truth surveyors @ \$12.5K	875,000
13 administrators @ \$25K/ annum	325,000
65 support staff @ \$10K/annum	650,000
16 specialists @ \$20K/annum	320,000
Fringes and Expenses	825,000
<u>Printing Costs</u>	2,220,000
Utilities and Misc. Supplies (10% Op. Expen.)	917,000
TOTAL OPERATING EXPENSES	10,000,000
TOTAL FIXED COSTS AND OPERATING EXPENSES	13,300,000

TABLE III. SUMMARY OF EODMS SYSTEM ALTERNATIVES

Alternative	Key System Characteristics	Evaluation
System A: An Evolutionary System Based on Present Institutions	<u>Control:</u> Public Sector <u>Management:</u> Federal In- teragency Council <u>Configuration:</u> Process- ing at National Dis- ciplinary Centers <u>Scope of Data:</u> Princi- pally Satellite and High-Altitude Air- craft Augmented to Permit Some Priority Product Production <u>Principal Variation Con- sidered:</u> Some State- Level User Centers	Federal Interagency Council fits current government structure; interagency arrangement may lack co- hesion, responsiveness; national disciplinary centers may prove cost- inefficient; state pro- cessing variation beyond means of most states

TABLE III. SUMMARY OF EODMS SYSTEM ALTERNATIVES (continued)

Alternative	Key System Characteristics	Evaluation
System B: A Natural Resources Information System with Interpretation at a National Center	<u>Control:</u> Public Sector <u>Management:</u> New Federal Department of Natural Resources <u>Configuration:</u> Processing at National Multidisciplinary Centers <u>Scope of Data:</u> All Data Pertaining to Natural Resources Management <u>Principal Variation Considered:</u> State Branches of National System Perform Some Functions	Federal Natural Resources Agency provides suitable focus for information products and coherent management. Takes major government effort to implement. Processing at multidisciplinary centers more cost-effective than at disciplinary centers. National centers may prove unresponsive to state and local concerns, with relatively little cost advantage over regional or large-state processing.
System C: A National Data System with Interpretation at Regional Centers	<u>Control:</u> Public Sector <u>Management:</u> New National Data Agency <u>Configuration:</u> Processing at Regional Multidisciplinary Centers <u>Scope of Data:</u> System B plus Socioeconomic Data <u>Principal Variations Considered:</u> 1. Some State-Level Processing 2. Federal Interagency Management	Cost-effective, coherent management possible; having a "super" government information agency likely to prove threatening and politically unacceptable; multidisciplinary regional processing seems to strike right balance in terms of technical capability, economics and responsiveness to users.
System B: A System under Private Sector Control	<u>Control:</u> Private Sector <u>Management:</u> New, Congressionally-Chartered "INFOSAT" Corporation <u>Configuration:</u> Flexible <u>Scope of Data:</u> Principally Satellite and High-Altitude Aircraft Augmented to Permit Some Priority Product Production <u>Principal Variations Considered:</u> 1. Two parallel systems: public serving public sector, private serving private sector. 2. System under public sector control with heavy private sector involvement.	Private sector system not likely to have sufficient incentive and reward for servicing "soft" state, local, regional user markets. Certain traditional government functions would need to be curtailed. Private sector likely to have major involvement in processing for large private-sector users and to perform several functions in a public sector system. These functions should be carefully delineated to avoid possible conflicts of interest.

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REINDEER RANGE INVENTORY IN WESTERN ALASKA FROM
COMPUTER-AIDED DIGITAL CLASSIFICATION OF LANDSAT DATA

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ABSTRACT

An inventory of reindeer-range resources has been conducted for the USDA Soil Conservation Service of 1.6 million hectares of wildlands in western Alaska using clustering techniques with digital Landsat data. Computer-aided digital analysis produced a provisional map of rangeland types which was used to design the field collection of vegetation and soil type data. This field data facilitated refinement of the inventory map and was used to describe the map units. The informational classes important to range resources were wet, moist and alpine tundra, tidal marsh, brush and open spruce forest.

A significant feature of the study was the extraction of acreage figures by administrative boundaries within the study area. In addition to soil and vegetation association map products (at scales of 1:250,000 and 1:63,360) acreage values were tallied from the digital data for each of the four grazing permit areas established by the Bureau of Land Management.

The boundaries of the four grazing permits were digitized from administrative maps and digitally overlaid to the classification results. The total pixels by class were tabulated by computer within each permit area. Line-printer maps of the classification were prepared to combine the classification results with the administrative boundaries. Each pixel inside the boundary was overprinted three times and the pixels outside were printed only once. The resulting map was used to establish the validity of the digitized boundary. The pixel counts were converted into acreage and percent-of-cover figures to provide the Soil Conservation Service with tabular results of the inventory. Tabular acreage figures and standard map products form an inventory data base to aid the range manager in the preparation of grazing plans.

1. INTRODUCTION

Reindeer herding in Western Alaska has a long and colorful history. Reindeer were first introduced from Siberia in the 1890's as part of a federal project to provide a source of milk, meat, clothing and transportation for Alaskan Eskimos. For some time the industry flourished, and at its peak in the 1930's, there were estimated to be over half a million reindeer in the territory of Alaska. A sharp decline followed, brought on in part by a change in federal policies, bad weather, overgrazing and poor market conditions. By 1950 the number of reindeer remaining in domestic herds had declined to approximately 25,000. [1]

Recently, renewed interest has developed in the the herding industry by the Northwest Alaska Native Association (NANA). NANA is one of the twelve regional native corporations established as part of the Alaska Native Claims Settlement Act. The corporation has obtained the use of two reindeer ranges, administered by the Bureau of Land Management (BLM) and is in the process of acquiring a reindeer herd. In support of these efforts NANA requested assistance from the United States Department of Agriculture's Soil Conservation Service (SCS) for planning and management of the industry. The first step of this program was to conduct a vegetation and soils inventory of a 1.6-million hectare area of range on the Seward and Baldwin Peninsulas.

The logistics of the range inventory presented a few problems. The area is quite large and remote. The short summer season combined with the inaccessibility of the region place some severe limitations on field work. Time and funds available were limited to the point that conventional techniques were not considered practical. For these reasons, the Soil Conservation Service entered into a joint feasibility study with the University of Alaska's Geophysical Institute to determine whether Landsat imagery could be used as the data base for range inventory. This study, carried out during the summer of 1975, proved favorable. [2] As a result SCS and the Geophysical Institute entered into a joint agreement to carry out an inventory of the entire range identified by NANA.

2. THE PHYSICAL SETTING

The study area, shown in Figure 1, includes the major portion of four Bureau of Land Management reindeer grazing permits which extend from the continental divide on the Seward Peninsula north to Kotzebue Sound, including the Baldwin Peninsula. The climate is transitional between Arctic, Continental, and Maritime with mean temperatures ranging from 10°C in July, to -23°C in January. Recorded extreme temperatures range from 29°C to -50°C . Total precipitation averages approximately 25 cm per year, including the annual snowfall of 91 cm. The area is predominantly underlain by permafrost limiting the percolation of water to within a few inches of the surface.

The main population center in the area is Kotzebue, the regional commercial and transportation center, with a population of 2000. The villages of Deering and Buckland have populations of 85 and 120 respectively and Candle, an active mining community is not occupied during the winter.

The study area consists of lowlands in the vicinity of Kotzebue Sound rising to rolling hills and outcrop capped highlands reaching elevations of approximately 600 meters near the divide. Tundra bordered with brush dominates the landscape. Wet tundra is found on the lowlands, mesic tundra on the rolling hills forms the transition to alpine tundra at higher elevations. Willow and alder are found along streams and gullies ranging from tall forms in better drained areas to decumbent forms in wet areas. Open spruce forest with tundra or brush understories is found on the hillsides in the southeast part of the study area. [3]

3. PROJECT OVERVIEW

Digitally processed Landsat data was used to generate a preliminary map of the study area. Computer processing was performed on the IDIMS System at Electromagnetic Systems Laboratories in Sunnyvale, California. Field investigation was conducted to define and describe the vegetation and soil classes from spectral classes on the computer generated map. (See Figure 2)

Three summer Landsat scenes were found with cloud free coverage of the study area. (See Table I) Color prints at 1:250,000 scale and digital tapes were ordered for these three scenes. A series of late winter scenes with low sun angles enhancing the landforms of the area were selected. Black and white band-7 1:250,000 scale prints of the winter scenes were acquired.

Based on the previous year's feasibility study, the color, and black and white Landsat imagery were photo-interpreted to produce a tentative vegetation and landform association map. The object of this analysis was to estimate the number of spectral categories in the summer data and make a tentative correlation with vegetation communities. Digital classification techniques were preferred for the actual inventory because of the improved spatial resolution (each picture element - pixel - is approximately 0.5 hectares) as well as the uniform mapping consistency leading to detailed inventory results. The digital classification technique used was basically an unsupervised approach. A

statistical clustering algorithm was applied to sample data sets selected randomly with specific additions based on the photo-interpretation analysis results.

After cluster statistics were derived, the entire scene was classified using a maximum-likelihood classification algorithm that assigned each pixel its most appropriate spectral class defined by the cluster statistics. The resulting classified Landsat scene was displayed on a TV monitor and compared to the photo-interpretation maps. From this evaluation and study of the cluster statistics it was apparent that the classes generated represented more detail than was required for the inventory. Using the TV display, spectral classes were evaluated and combined to reduce the total number of map categories. Figure 3 shows two dimensional "cluster plots" that illustrate graphically the spectral clusters and the final color combinations for one of the Landsat analyzed during the study.

The classification procedure was performed independently for each of the three summer Landsat scenes. Based on the feasibility study and the photo-interpretation analysis, tentative cover type assignments were made and colors assigned to the spectral classes. Each Landsat scene covered a different geographical area with somewhat different vegetation characteristics, so no attempt was made to force the same number of spectral clusters from each of the scenes. Geometrically corrected hard-copy color products were generated at scales of 1:250,000 and 1:63,360 for use in the field. (See figure 4)

4. FIELD DATA COLLECTION

A four man team consisting of two range specialists, a soil scientist and Landsat investigator spent one month in the field collecting vegetation and soils data. The field crew, using a helicopter for transportation, treated the Landsat color products as preliminary maps. Field work consisted of identifying species [4] [5], recording plant productivity and making soils descriptions to define the map units. Plant productivity was determined by a double sampling technique using an ocular estimate and clipped weight procedure. [6] From the field observations, the team described the map units, noted the variability and looked for conflicts between plant/soils types and the Landsat classification.

The helicopter played a key role in the field work. Map units for this level of inventory cover from tens to hundreds of hectares. These units are readily identifiable from the air, giving the field crew confidence that they have located the map unit they are seeking. In the tundra, differences between plant communities are often very subtle--the traveler on foot may find it difficult or impossible to tell when he has passed from one community into another. The aerial vantage point from the helicopter, with preliminary maps and the ability to land almost anywhere, resulted in the efficient collection of ground data. This procedure enabled the field crew to cover the 1.6-million hectare area in one month.

5. RESULTS

The soil and vegetation types identified by the field crew are summarized in Table II. Some of the features in the table are the common name used in the field, the landform or terrain type for the group, a plant community and soil descriptions and the "color" or colors for each of the Landsat scenes corresponding to the cluster groups in Figure 3(b). This table is preliminary. The final map units and descriptions will be based on detailed examination of the field data.

Inspection of Table II reveals a number of interesting details: (1) Colors on different Landsat scenes do not always match (i.e., line 5 tussock tundra is represented by both dark green and light green). This is not surprising since the scenes were processed separately and the color assignment was made to maximize the differences with each color product. (2) Some plant communities and soils are represented by more than one spectral class (i.e., yellow and white on scene 2183 are both associated with drained lakes). For these cases, there were distinctions between the two classes too fine for

separation at this level of survey. They were combined and treated as a single class. (3) Finally, some spectral categories were found to represent more than one vegetation and soil type. The worst offender was the category represented by yellow in scene 2183 which corresponds to tidal flats, drained lakes, lava flows, granite outcrops and old forest fires. These cover types had similar reflectance characteristics. However, taken together they comprise less than 3% of the study area. This problem was anticipated at the time of the analysis on the TV display and confirmed in the field. In each case other criteria were developed for separation of the cover types from additional data sources such as topographic maps and winter Landsat imagery.

6. INVENTORY PRODUCTS

The inventory results are being prepared in map and tabular formats for the range manager and other users.

Map Generation. Maps are being manually transferred from the computer generated color products to mylar overlays. A map of the entire study area has been prepared at a scale of 1:250,000 with generalized map units of similar vegetation and soil types. The final map will be on a black and white Landsat imagery base. More detailed maps of the individual BLM reindeer grazing areas will be produced at a scale of 1:63,360 on the USGS topographic map base. At this scale detailed map units will show features such as riparian brush communities.

Tabular Results. Tabular summaries of the inventory results are being derived from the digital data for each of the BLM grazing permits. The resource planning and management user would like to know the areal extent of the vegetation and soil types available. Traditionally this information has been derived as a secondary product from inventory maps. The inventory data base is in digital format, stored on a computer compatible tape. A tabular summary is easily produced from this digital format. The Landsat pixel (0.5 hectares) is much smaller than the minimum size map units (> 10 hectares), which allows greater detail in the tabular summary.

Each BLM grazing permit boundary was drawn on a 1:250,000 scale topographic map. The boundary was then broken into line segments which could be more easily digitized. Control points were selected from line printer maps of the satellite data at a scale of 1:18,661, and located on the topographic map. The control points were used to define an affine transformation used to superimpose digitized boundary points on the digital data. A program was developed to sum the pixels within each grazing permit by spectral class by generating points on each Landsat scan line around the boundary, removing all single points where the boundary is tangent to a scan line, sorting the remaining points, and then counting pixels between pairs of points. Acreage values were computed and recorded. As discussed previously, in the cases where a spectral class was not unique to a specific vegetation and soil type, estimates were made from the color products and maps to establish the percentage of the spectral class belonging to a given cover type. The results of this process for the "Karman" grazing permit are presented in Table III.

As a control for the registration procedure, a lineprinter output of the classification results was generated with pixels inside the boundary overprinted three times and those outside the boundary printed only once. The area inside the boundary was therefore shaded and could be visually examined to verify the location of the boundary relative to the Landsat classification results.

7. CONCLUDING REMARKS

This project used digitally classified Landsat data as a tool for resource inventory. Computer classification was combined with information gained from the feasibility study and a manual interpretation of the imagery. Computer aided analysis was used for the mapping due to the high spatial resolution and uniform treatment of data. The computer generated preliminary map provided a spatial model of the study area, which gave direction to the efforts of the

field crews. Data were collected in the field to describe map units and to identify and resolve conflicts between the cover types and the preliminary map.

After the field season, final maps were generated from the Landsat digital classification. These maps are a refinement over the original classification products. The maps are being generated manually, but the investigators believe that this process may be accomplished in the future with the aid of a computer, thus giving further savings of money and preparation time. The projected cost of this study is currently \$130,000, including data, computer processing, analysis and field labor and helicopter time.

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TABLE I. LANDSAT SCENES USED IN THIS STUDY

Summer	
1709-21504	2 July 1974
1760-21320	22 Aug. 1974
2183-21470	24 July 1975
Winter	
1565-21543	8 Feb. 1974
1581-21425	24 Feb. 1974
1582-21481	25 Feb. 1974

TABLE II. PRELIMINARY PLANT AND SOIL TYPES (SEPTEMBER 2, 1976)

COMMON NAME	LAND FORM	PLANT COMMUNITY	SOIL	LANDSAT SCENE COLOR		
				2183	1760	1790
1) Tidal Flats	Tide Flats	90% <u>Carex ramenski-Potentilla egedii</u> , 10% <u>Elymus mollis</u>	Histic pergelic cryaquepts (Sapric) -decomposed-	Yellow	Brown	Yellow/brown
2) Drained Lakes	Drained Lake	<u>Carex aquatalis</u>	Pergelic cryofibrists (Fibric material) deep peat	Yellow/White		Tan
3) Low Center Polygons	Low Center polygon in drained lake	80% <u>Carex aquatalis-Carex rotundata</u> , 20% ice wedges with tussocks	80% pergelic cryofibrists 20% Histic pergelic cryaquepts	Olive	-	Dark Green
4) Alluvial Flood Plain	Flood Plain	high brush-alder/willow and/or white spruce	Pergelic cryorhents Pergelic cryaquepts	Red/brown	Red/brown	Red
5) Tussock Tundra	Gentle slopes, and rolling hills and high center polygons	<u>Eriophorum</u> tussocks and low shrubs	Histic pergelic cryaquepts (Fibric and Hemic)	Dark green	Dark green	Light green
6) Upland Tussock Tundra	Gentle Slopes and rolling hills	<u>Carex</u> , lichen and low shrubs	Histic pergelic cryaquepts (Fibric and Hemic)	-	Light green	-

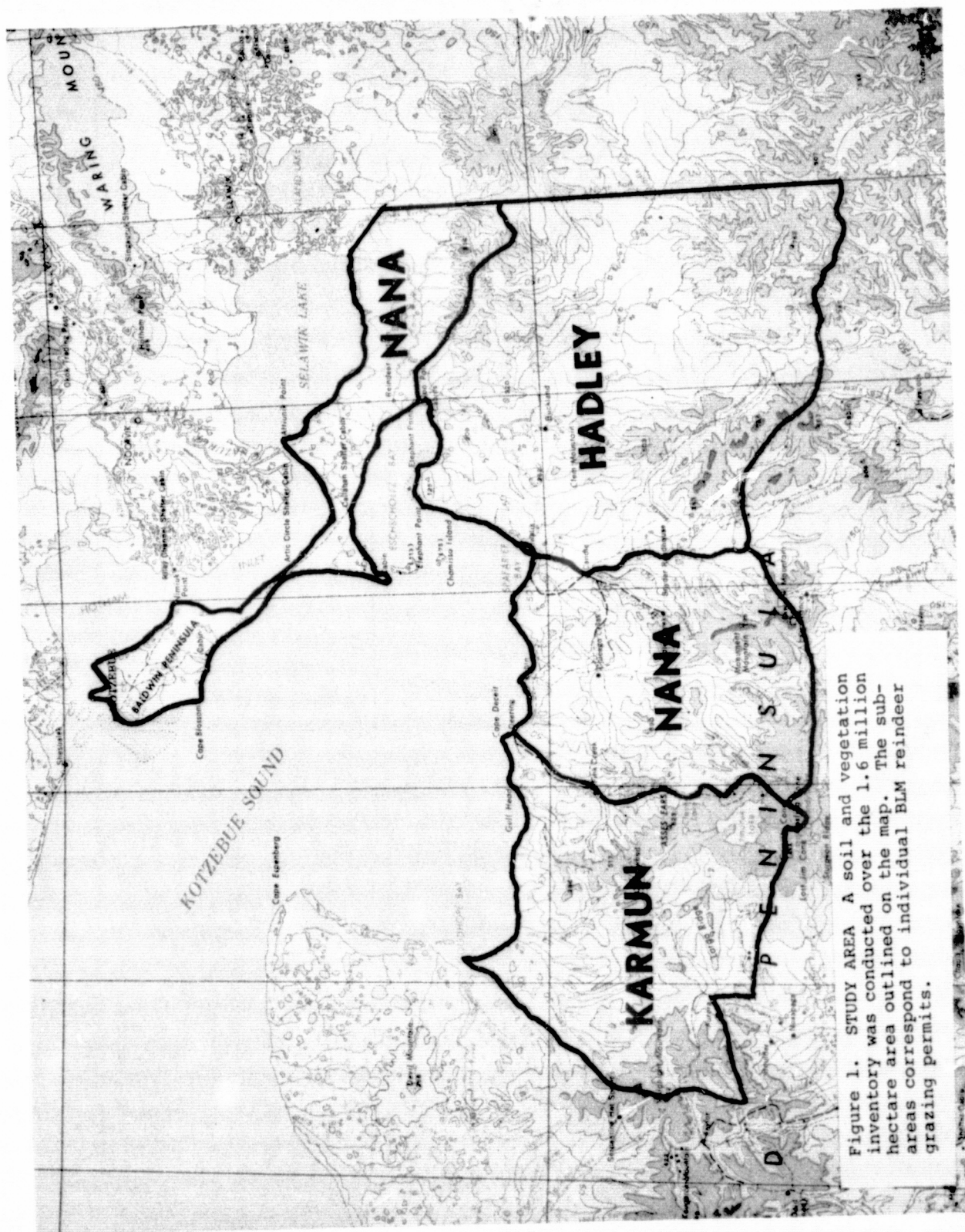
TABLE II. (Cont'd)

	COMMON NAME	LAND FORM	PLANT COMMUNITY	SOIL	LANDSAT SCENE COLOR		
					2183	1760	1790
7)	Mountain Meadow	Mnts. and hills (generally on slopes with solifluction lobes)	<u>Carex biglowii</u> , <u>Salix planifolia</u> (grassland aspect)	Pergelic cryaquepts	Light green	Light green	-
8)	Bald slopes (Alpine Tundra)	High ridges and hill tops above line	<u>Dryas-Carex nardina</u> , <u>Carex vaginata</u> , lichen	Pergelic cry-umbrepts Pergelic cryo-borolls	Pink	Pink	-
9)	Bare ridges, rockland and lave plateau	Hill tops and Basalt flow	<u>Dryas</u> - lichen, <u>Cassiope</u> 60-70% fragments	Pergelic cryo-rthents Pergelic cry-umbrepts	Yellow/white	-	-
10)	Tall Shrub Tundra with shrubs	Gentle slopes and rolling hills	<u>Eriophorum vaginatum</u> and <u>Carex</u> - low shrubs with intermittent taller shrubs (Willow and/ or alder .75-1 m)	Histic per-gelic cryaquepts (Fibric and Hemic)	Orange	Orange	Red
11)	Tall Shrub	Steep Hillsides	<u>Alnus crispa-Salix planifolia</u> , <u>Carex biglowii</u> > 1 meter)	Pergelic cryaquepts	Red	Red	Red
12)	White spruce Shrub	Hillsides Southeast quadrant of Study area	<u>Picea glauca</u> <u>Salix planifolia</u> , <u>Alnus crispa</u> , <u>Betula glandulosa</u>	Pergelic cry-umbrepts Pergelic cryo-borolls	Brown/red	Brown	-
13)	Recent Burns				Yellow	Brown	Brown

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TABLE III. KARMAN REINDEER GRAZING PERMIT TABULAR SUMMARY
OF PLANT/SOIL TYPES

<u>TYPE</u>	<u>%</u>	<u>HECTARES</u>
Tidal Flats	0.8	3,000
Drained Lakes	0.4	1,500
Low Center Polygons	2.6	9,900
Tussock Tundra	51.2	194,400
Mountain Meadow	12.1	46,000
Bald Slopes	0.5	1,900
Bare Ridges, Rockland	7.1	27,000
Tussock Tundra with Shrubs	18.8	71,400
Tall Shrubs	3.0	11,400
Water	2.7	10,300
Miscellaneous Other Types	0.8	3,000
 TOTAL	 100.0%	 379,800



KOTZEBUE RANGE STUDY PLAN

by the: Soil Conservation Service &
the Geophysical Institute, U.A.

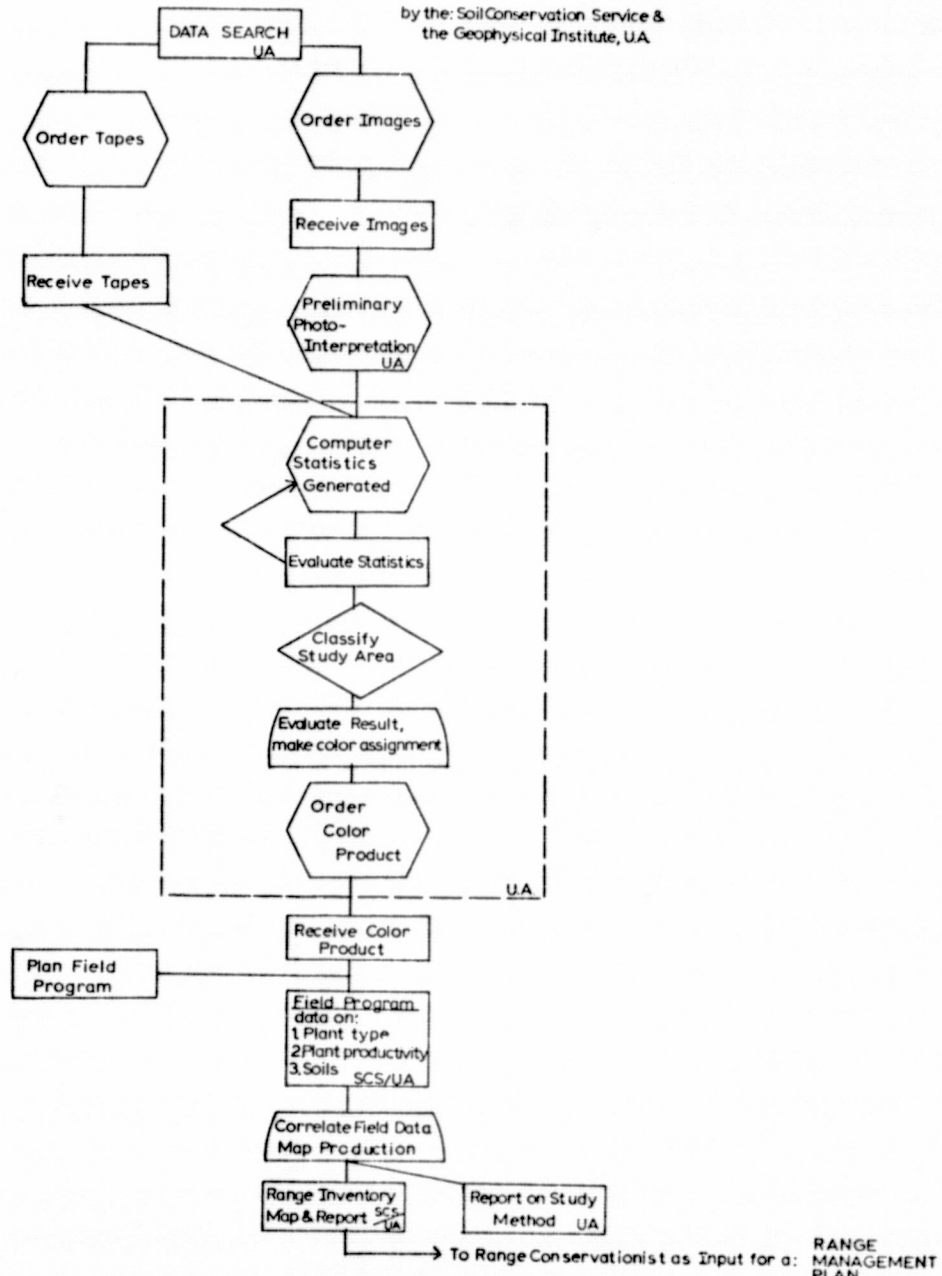


Figure 2

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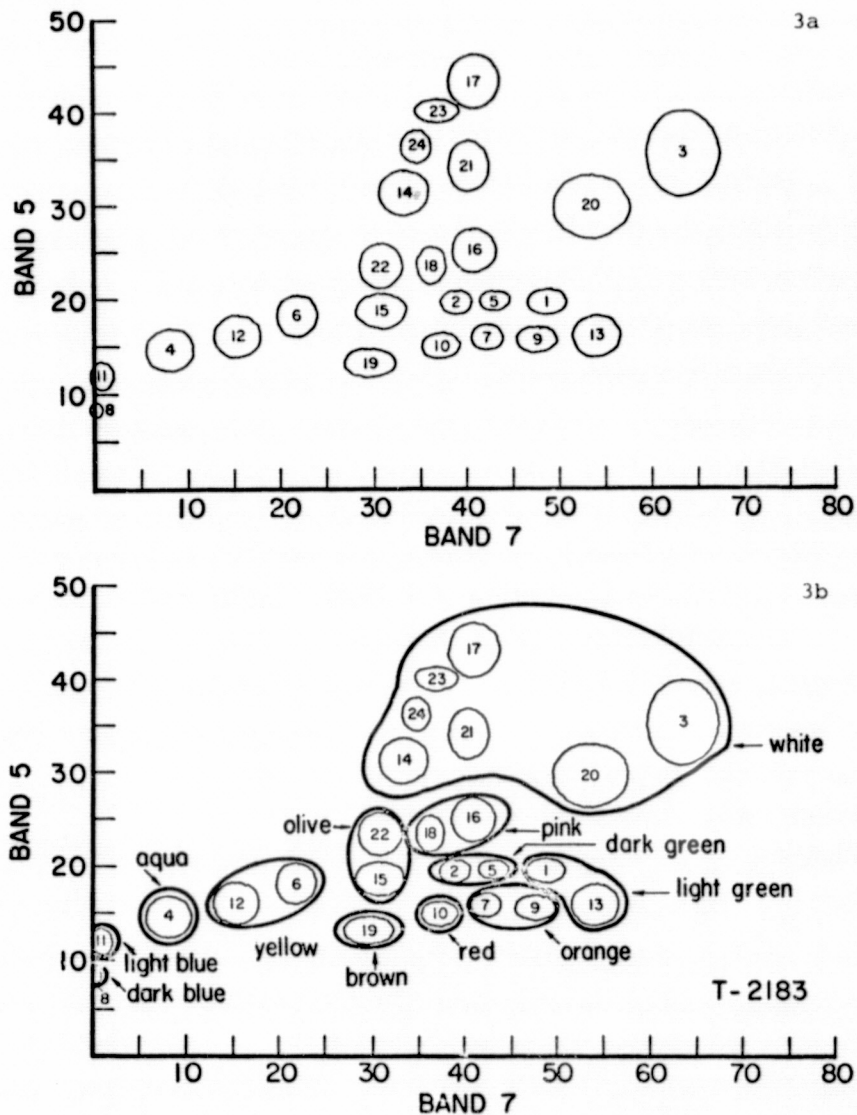


Figure 3. CLUSTER PLOTS These diagrams give a two dimensional representation of the cluster groups from one of the Landsat scenes classified. The original clusters appear in 3a. Final combined classes are shown in 3b with the corresponding color used to represent the class in the color product.



Figure 4. COLOR PRODUCT This is a black and white reproduction of one of the "color products" generated during this study. The image is a subsection of Landsat scene 1709-21504. Enlargements were made to scales of 1:250,000 and 1:63,360 for use in the field.

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REMOTE SENSING EXPLORATION FOR
METALLIC MINERAL RESOURCES IN
CENTRAL BAJA CALIFORNIA

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ABSTRACT

Remote sensor data (primarily Landsat) was analyzed by photogeologic and computer-assisted enhancement techniques to evaluate the metallic mineral potential of Baja California. Overlays were prepared at 1:1,000,000 and 1:500,000 and included known geologic relationships and mineral occurrences; lineament, drainage and structural patterns; tonal anomalies and IMAGE 100 enhancement results.

Computer-assisted enhancement and classification of the test sites was performed using General Electric's IMAGE 100 system to identify subtle tonal anomalies thought related to mineralization using known sites as analysis guides. Data sources were correlated and ten 12 km x 12 km targets were selected which displayed the greatest concentrations of mineral indicators or "ore guides". The probability for mineralization within the study area was quantified by assigning an arbitrary "score" to these indicators proportional to the degree to which they indicated favorable conditions for mineral emplacement. Mineral potential maps of Baja California were generated from these analyses and the ten highest priority targets visited in November 1976 with the kind support of the Mexican Government's Consejo de Recursos Minerales.

Preliminary assay results (atomic absorption analysis) for the samples recovered showed moderate to high geochemical anomalies for Copper (10 of 12 samples), Zinc (3 of 12 samples) and Lead (4 of 12 samples).

1. INTRODUCTION

The purpose of this study is to test a multi-faceted approach to the exploration for metallic mineral resources using remotely sensed data (primarily Landsat), "ground truth" (including published and unpublished information), conventional photogeologic interpretation and advanced computer-assisted image enhancement and classification techniques. The study is based on the philosophy that individual information sources are generally incomplete by themselves; it is the methodical compilation and evaluation of each of these (analyzed within the context of all information inputs) that provides a technique for evaluating the "mineralization potential" of an area of interest (Figure 1).

Baja (lower) California comprises a narrow 760 mile long peninsula associated with the western edge of the North American-Pacific crustal plate boundary. In general, it is a geological extension of southern California (e.g. the Peninsular Ranges and Sierra Nevada batholith) but has been studied at little more than a reconnaissance level. Historical accounts describe some mining activity (especially Copper, manganese, gold and silver) back to the late 1700's, resulting in small settlements and nearby Spanish missions. With the exception of a few mining districts such as El Triunfo, Boleo and Lucifer, mineral deposits of major economic significance have not been reported.

Because of general geologic similarities with southern California mining districts and inaccessibility due to harsh climate and rugged terrain, Baja California is especially well-suited for remote sensor based mineral exploration, where photogeology and computer-assisted image analysis can be combined to "prospect" vast regions. Further, the dry climate characteristic of most of the region inhibits vegetation and minimizes cloud cover, both factors which hinder geological analysis.

The geologic history of the region is characterized by a "mid-Mesozoic" and a "mid-Cenozoic" event by Gastil *et al.* (1975). The earlier event is documented in the rock record by "volcanic strata of the island arc type, regional metamorphism and the emplacement of pervasive granitic rocks", accompanied by severe structural deformation, uplift and erosion. The later event "involved the accumulation of a wide variety of volcanic rocks, minor(?) metamorphism and granitic emplacement, and the creation of the Gulf of California, a mobile tectonic belt." Gastil considers this second event, initiated near the beginning of Miocene time, to be continuing. These two events divide the geological history of Baja California into distinct pre- and post-batholithic intervals.

A review of the literature reveals two trends in the application of aerial and satellite remote sensing to mineral exploration—a continuing improvement in sensor and data interpretation technology, and an increasingly greater reliance on remotely sensed information to reduce surface and subsurface exploration costs to a minimum.

The rationale behind detecting mineral deposits by satellite sensors stems from two general theories related to mineral emplacement:

1. Zones of crustal weakness - faults, fractures or brecciated rock may serve as conduits for mineralizing fluid migration or magma emplacement.
2. Surface structural or tonal anomalies - possibly resulting from contact metamorphism, weathering (oxidation and secondary enrichment) or characteristic soil and vegetation development can be associated with geochemical or geobotanical manifestations of ore body emplacement.

From these basic assumptions, geologists utilizing satellite and aerial photography or imagery have recognized four indicators thought useful for locating mineral deposits:

- 1) lithologic associations; 2) structural associations, especially the relationship of ore bodies to geologic features; 3) geobotanical or geochemical alteration; chemical changes resulting from metamorphism, vegetation stress, secondary enrichment and/or weathering; or 4) "lineament" and "curvilinear" feature density and distribution (Table 1).

2. METHODS OF INVESTIGATION

2.1 PHOTOGEOLOGY

Baja California was examined for surface indicators of mineral deposits using visual photogeologic interpretation of Landsat imagery and computer-assisted analyses of Landsat digital tapes (CCTs) to enhance, detect and classify land surface features using the "IMAGE 100" multispectral image analysis system. The visual photogeologic interpretation consisted of three steps: the detection, classification and identification of tonal (density) values, textures, shapes, patterns and orientations of image elements. These are related to terrain parameters such as structural and geomorphic features, lithologic associations and soil/rock distributions. These associations were combined with ground truth and used to postulate relationships between targets on the ground and remotely sensed information.

Overlays of the central Baja California test sites were prepared at scales of 1:1,000,000 and 1:500,000; the largest scale at which Landsat data can be analyzed without major degradation of image resolution (Welch, 1973). Transitions between the Landsat working scales (1:1,000,000 and 1:500,000) and the various map scales and projections of supportive data were performed optically. Information from the smaller scales was enlarged to the 1:500,000 format by optically projecting the appropriate overlay and redrawing the information at the desired scale using the projected image as a base. Control reference points in both the x and y directions insured optimum geometric registration.

Overlays were correlated and the evidence for mineralization displayed in each information category (i.e., lineaments, structure, lithology, drainage patterns, etc.) was interpreted in the context of all other information categories, and the likelihood of mineralization evaluated.

2.2 IMAGE 100 ANALYSIS

To complement the visual photogeologic interpretation, computer-assisted analyses were conducted using General Electric Company's "IMAGE 100", a multispectral user interactive image analysis and classification system at GE's Image Processing and Analysis Center, Beltsville, Maryland. While automated procedures have not as yet been able to match the pattern recognition and association capabilities of a human interpreter, computer-assisted techniques can discriminate and enhance subtle spectral variations. Since each Landsat image contains approximately 16×10^6 data bits, automated processing and analysis techniques are required for maximum information extraction within practical time constraints.

The system can detect subtle variations in the radiometric properties of an image, and enhance these differences so that they can be detected by the analyst. It will also classify the image by these spectral characteristics (either enhanced or unenhanced), so that regions having like "signatures" can be identified. Mineral concentrations at depth are often accompanied by secondary surface indicators, many of which (e.g., tonal anomalies associated with geochemical or geobotanical "stress" - gossans or alteration aureoles) can often be detected by this type of multispectral computer-assisted image analysis.

Analysis techniques employed for the IMAGE 100 phase of this study were designed to 1) emphasize structural information which would verify or supplement results of the photogeologic interpretation, and 2) lead to the detection of tonal anomalies which could be related to geochemical or geobotanical indicators of mineralization.

Mineral Potential Evaluation

The detection of potentially significant metallic mineral concentrations in Baja California was based on surface indicators or "ore guides" previously found useful for mineral exploration by remote sensing techniques. Specific indicators were selected from previous work, NASA significant results of investigations and personal experience (Table 1).

The probability for mineralization within the study area was quantified by evaluating indicator criteria and assigning each a value determined by the degree to which it indicated favorable conditions for mineral emplacement. For example, an area containing obvious lineament (fault or fracture) intersections is more apt to provide migration channels for mineralizing fluids than an area devoid of them; hence, it would receive a higher score in this category. Scoring criteria for each category shown in Table 2.

Categories of ore guides were weighted according to the type, detail and quality of data available, successful use in previous studies, and significance of the processes with which they are associated.

Initially, the entire peninsula was divided into 25×25 km grid units using the 1:1,000,000 Landsat mosaic as a base. Each grid element was evaluated separately and assigned a mineral potential score based on the photointerpretation of surface mineral indicators present (Figure 2). From these evaluations, a first approximation of the overall potential for metallic mineral occurrence was achieved and a primary study area selected for detailed analysis. As the evaluation of individual grid elements progressed, it became clear that a simple binary (favorable/unfavorable) evaluation system would not provide the degree of target "favorability" discrimination required for actual exploration programs. To correct this, specific degrees of favorability were established (Table 2).

The criteria thought to be most useful for determining the overall mineralization potential of the study area were divided into three categories: photogeology, IMAGE 100 and ground truth. IMAGE 100 analyses were limited to central Baja, after initial targetting of the entire peninsula was done by photointerpretation. The region was evaluated in 3 separate sections (northern and southern at 1:1,000,000 and central at 1:500,000) because data inputs varied slightly for each.

Prime exploration targets were selected separately in each of the geographic regions. Those designated in central Baja California were based initially on favorable areas delineated in the northern and southern 1:1,000,000 scale maps. These targets were refined by photogeologic interpretation at 1:500,000, IMAGE 100 analysis and supporting ground truth. Each grid unit was assigned a "mineral potential score" based on the aggregate number of positive indicators displayed.* The distribution of scores was plotted and grid units categorized into five levels:

*(see figure 2)

<u>Category</u>	<u>Potential</u>	<u>North</u>	<u>South</u>	<u>Central</u>
A	Highest Priority	8.9	17.2	9.4 % of total
B	Excellent	10.9	19.1	12.5
C	Some Interest	21.9	18.3	18.4
D	Little Evidence	19.4	15.2	28.8
E	Lowest Priority	38.9	30.2	30.9
		100.0	100.0	100.0 Total
Total number of grid units:		286		160

The primary target areas lie in central Baja California between the Santa Clara Desert and the Gulf of California, roughly between Bahia de los Angeles to the north and Santa Rosalia to the south (Figure 1). This region was selected for these reasons:

- 1) Results from the initial analyses at 1:1,000,000 indicated that metallic mineral deposits could exist in several localities within the area and that many of these sites were accessible for field checking.
- 2) Some authors (Gastil *et al.*, Wissler, 1954) recognized three major mineral provinces occurring in this region: the volcanic copper-iron, schist-gold, and cenozoic hydrothermal provinces associated with metavolcanic, metasedimentary and cenozoic volcanic structures, respectively. These provinces occur in broad belts trending generally NW-SE, and exploration targets were selected in each to evaluate the mineral exploration techniques developed in this study in a range of geologic settings and structural styles.

Results

Twelve (12) surface samples were collected in November 1976 from 10 sites and analyzed using a Jarrell-Ash model 800 Atomic Absorption spectrophotometer.

In addition, the Consejo de Recursos Minerales, Mexico City analyzed splits of the samples for comparison purposes. Additional sample analyses are presently being undertaken (Table 3).

These results, while preliminary, seem to demonstrate that a combined approach using all available remote sensor and ground truth data can be usefully incorporated into a mineral exploration program at the reconnaissance level.

The sample collected generally represented only one point in a 12 km x 12 km grid cell. The cells yielding samples of interest should be resampled more extensively, with geophysical work and exploratory drilling as a logical follow-on as appropriate.

Acknowledgements

I am grateful to Ing. Guillermo P. Salas, Director-General of the Consejo de Recursos Minerales and to Ing. I. Restovic and G. Silvera for supporting the field investigation. This work is part of a PhD dissertation effort presently being completed at the Department of Geology, University of Delaware under the direction of Dr. Allen M. Thompson.

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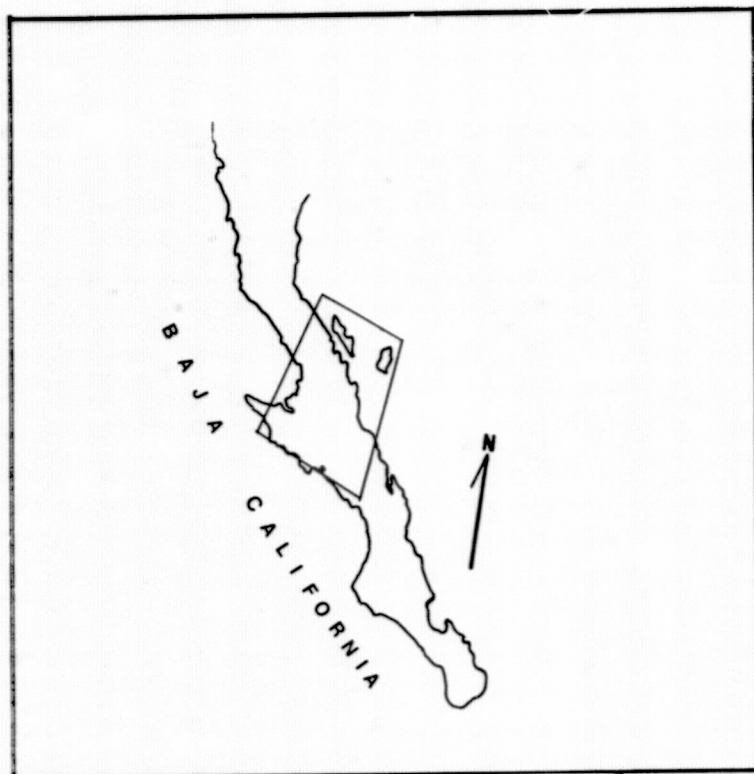


FIGURE 1. GENERAL STUDY AREA. The peninsula is approximately 760 miles long. Central Baja test site is within the rectangle.

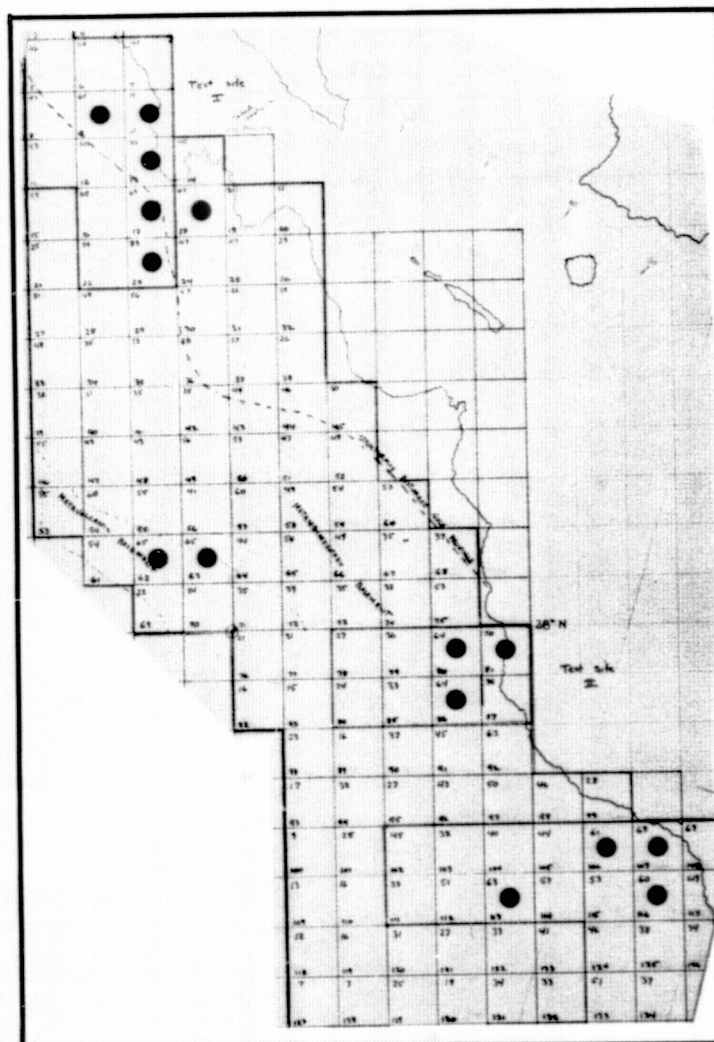


FIGURE 2. MINERALIZATION POTENTIAL MAP FOR CENTRAL BAJA CALIFORNIA. Original map was prepared at a scale of 1:500,000 using all data inputs. Black dots show grid cells field checked. Evaluation score shown in upper left corner of 12 km x 12 km grid cell.

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	HAKES & WEBB (1962)	STRATTON <u>et. al.</u> , (1970)	RECASSIO (1972)	SHORT & LONNAN, (1973), SHORT, (1974)	JENSEN (1974)	KNEPPER (1974)	LIGGETT <u>et. al.</u> , (1974)	BAKER (1975, 1976b)	CHEESEMAN, (1975)	ROMAN (1975)	HALBOUYT (1976)	SHORT & STEWART (1976)	TOTAL	THIS STUDY
<u>GEOLOGIC STRUCTURE</u>														
Linear Features (Density, Intersections)	X		X	X	X	X	X		X	X	X		9	X
Curvilinear or Circular Features						X	X				X	X	4	X
Structural Associations		X						X			X		3	X
Folds							X						1	
Volcanic Centers, Collapse Structure						X	X	X					3	X
Shallow Intrusives, Domes						X	X	X					3	X
Veins, Dikes, Plutons	X					X	X	X					4	X
<u>GEOMORPHIC FEATURES</u>														
Drainage Patterns	X	X					X	X					4	X
Weathering, Erosion		X	X				X						3	X
Soil Anomalies	X	X											2	X
<u>LITHOLOGY</u>														
Rock Associations	X	X		X			X				X		5	X
Bleaching, Recrystallization							X						1	X
<u>SURFACE ALTERATION</u>														
Hydrothermal Alteration	X	X		X	X	X	X	X	X	X	X		10	X
Gossan, Iron Oxides	X	X		X	X		X	X	X	X		X	9	X
Copper Carbonates, Clay Minerals, Silicified Rocks, Sulfates, Sericite	X	X					X					X	4	
Contact Zone Variations											X		1	
Mineralization	X			X	X	X	X						5	X
<u>VEGETATION</u>														
Enhancement or Stress	X	X					X	X			X		5	X
<u>SOIL MOISTURE</u>														
<u>THERMAL ANOMALIES</u>														
Radiogenic	X	X					X						3	X
Exothermal			X				X						2	
Thermal Inertia	X	X								X			3	
<u>AEROMAGNETICS</u>														
	X												1	
<u>BOUGER GRAVITY</u>														
														X

TABLE 1. FAVORABLE MINERAL DEPOSIT INDICATORS AS REPORTED IN THE RECENT LITERATURE

MINERAL POTENTIAL EVALUATION SCORE: (Baker, 1977)			1:1,000,000	1:500,000	(score assigned)
<u>LINEAMENTS</u> (from photogeology and ground truth)					
type:	probability:	density:			
single	low	---	2	2	
single	high	---	5		
multiple	low	low	7	4	
multiple	high	low	9		
multiple	high	high	10	8	
single intersection	low	---	12		
single intersection	high	---	15	12	
multiple intersections	low	low	17		
multiple intersections	high	low		14	
multiple intersections	high	high	20	16	

<u>GEOLOGIC STRUCTURE</u> (from photogeology and ground truth)				
Flat terrain- no obvious structure (buried or surface)	3	1		
Some suggestion of structure at depth; gentle topography	5	3		
Typical structural expression for region	7	5		
Favorable structural relationships, some evidence for buried structure	9	7		
Optimum structural relationships; e.g. margin of pluton, shear zones, anomalous disruption in regional patterns	12	10		

<u>LITHOLOGY</u> (from photogeology and ground truth)				
Surficial unconsolidated materials: alluvium, colluvium, terrace gravels, etc.	2	2		
Consolidated/semiconsolidated marine & fluvial deposits	4	4		
Widespread relatively homogeneous extrusive igneous rocks	6	6		
Complexly interrelated igneous, metamorphic and altered rocks	10	8		
Margin of batholith, known host rock,highly altered regions, unusual tonal or textural anomalies	12	10		

<u>IMAGE 100: ENHANCEMENT TECHNIQUES</u> (contrast stretch, ratio, color and tone variation, level slice...)				
Cell within broad enhanced area		2		
Cell within restricted enhanced area		4		
Distinct correlation with enhanced area and general area of mineralization		6		
Some correlation with enhanced signature over known mineral occurrence		8		
Discreet signature associated with known ore body		10		

<u>IMAGE 100: CLASSIFICATION TECHNIQUES</u> (supervised, unsupervised, two dimensional projection)				
Area of interest corresponds to broad theme		2		
Area of interest within broad theme also encompassing mineralized region		4		
Probable correlation of area and signature related to mineralized region		6		
Distinct signature related to mineralized region		8		
"Tight" signature restricted to ore body and area of interest		10		

TABLE 2. MINERAL POTENTIAL EVALUATION CRITERIA. Most important factors considered during the compilation of photogeologic, Image 100 and ground truth data. Northern and southern Baja California were evaluated at 1:1,000,000 using a grid of 25 km². A subsite was selected in the central portion of the peninsula and evaluated at 1:500,000 using a grid size of 12 km².

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TABLE 2 (continued). SUMMARY OF ALL DATA SOURCES UTILIZED, AND EVALUATION SCORE ASSIGNED.

CRITERIA FOR TARGET SELECTION	EVALUATION SCORE
• LINEAMENTS (FAULTS & FRACTURES)	20
• GEOLOGIC STRUCTURE	12
• ROCK TYPES & ASSOCIATIONS	12
• VOLCANIC TRENDS	10
• DRAINAGE PATTERNS	12
• SURFACE TONAL ANOMALIES	6
• HEAT CAPACITY, DIURNAL TEMPERATURE VARIATION	4
• DISTRIBUTION OF KNOWN DEPOSITS	12
• BOUGER GRAVITY & MAGNETICS DATA	12
MAXIMUM EVALUATION SCORE:	100

	Sample	Cu (A)	Cu (B)	Zn (B)	Pb (B)	Mo (B)	Ag (B)
	1	<u>180</u>	53	62	18	24*	1*
denotes concentration factor 2x: ____	2	100	43	40	9	18*	2*
denotes concentration factor 5x: (*)	3	80	39	71	10	26*	1*
	4	<u>140</u>	52	45	5	26*	2*
(A)=samples run at University of Delaware	5	120	73	65	59*	20*	1*
(B)=samples run by Consejo de Recursos Minerales, Mexico City	6	130	34	56	6	24*	2*
	7	130	41	59	92*	16*	1*
<u>RESULTS</u> in parts per million except where indicated	8	576*	<u>222</u>	.13%*	50*	18*	2*
	9	.3+%*	31	.51%*	133*	18*	3*
	10	450*	39	42	2	18*	2*
	11	.12%*	63	<u>265</u>	6	70*	2*
	12	370*	<u>167</u>	46	7	22*	2*
Average Crustal Skinner (1969)		58		82	10	1.2	.08
Abundance (ppm) Baumann (1976)		70		80	1.6	-	.1

TABLE 3. ATOMIC ABSORPTION ANALYSIS. Preliminary results. Variations in Cu analyses may be due to sample preparation or analysis techniques. They are being rerun but are included here for completeness. Hg, Ni and other selected metals will be run as well.

054
N78-14518

INVESTIGATION OF THEMATIC MAPPER SPATIAL, RADIOMETRIC,
AND SPECTRAL RESOLUTION*

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ABSTRACT

The objective of the investigation reported here was to provide additional empirical evidence for the definition of system specifications for the Landsat Follow-On Thematic Mapper (TM) and other future space MSS sensor systems. Specific sensor parameters addressed were spatial resolution, radiometric sensitivity, and to a lesser degree spectral bandwidths and locations.

The study used selected available aircraft MSS data, characterized by narrow spectral bands, fine spatial resolution, and high signal-to-noise, as the basis for simulating spacecraft TM data of various spatial resolutions, radiometric sensitivities, and sets of spectral bands. The primary measure used in evaluating the effects of varying spatial and radiometric resolutions was agricultural crop mensuration accuracy using automatic (computer) information extraction techniques.

From the spatial resolution study, definite improvement using 30-40 meter resolution over present Landsat-1 resolution and over 50-60 meter resolution was observed, using crop area mensuration as the measure. Simulation studies carried out to extrapolate the empirical results to a range of field size distributions confirmed this effect, showing the improvement to be most pronounced for field sizes of 1-4 hectares (the average field sizes found in most of Western Europe and India, for example). The radiometric sensitivity study showed significant degradation of crop classification accuracy immediately upon relaxation from the nominally specified values of 0.5% noise equivalent reflectance. This was especially the case for data which were spectrally similar such as that collected early in the growing season and also when attempting to accomplish crop stress detection. Spectrally, all of the 6 proposed TM spectral bands were shown to be of importance at some time during the growing season and together to provide performance as good as the six optimum bands of the aircraft data at each time. Distinct problems occurred in using (with other bands) a thermal band whose spatial resolution is 3 to 4 times that of the other bands; oversampling of the thermal band did not alleviate this problem. The 0.74-0.91 μm band was seen to be important for detection of crop stress condition.

*The investigation reported on herein was supported by the NASA Lyndon B. Johnson Space Center under Contract NAS9-14819.

1. INTRODUCTION

The heart of the proposed Landsat Follow-On satellites, the next generation in earth resources monitoring, is a multispectral scanner referred to as the Thematic Mapper (TM). The concept of a Thematic Mapper is as its name implies -- a sensor whose use would result in a mapping or description of the scene on the basis of the themes or subjects in the scene, mainly utilizing automatic information extraction techniques to produce final data products; further, it is anticipated that the greatest benefit from the TM will come from its use in world-wide agricultural surveys. Recent NASA efforts were aimed at finalizing the technical specifications for TM, with emphasis on automatic machine processing of TM data for agricultural applications.

The objective of the investigation reported here was to provide additional empirical evidence for the definition of TM and other, future, space multispectral sensor systems. Specific system parameters addressed were spatial resolution, radiometric sensitivity and, to a lesser degree, spectral bandwidths and locations. By the time of this investigation the preliminary specifications for TM had already been addressed by the activities of two technical study groups [2,3] and in a previous empirical study [1]. That study, carried out at ERIM, related sensor parameters to performance errors in terms of probability of misclassification and acreage measurement errors. The study reported here extends the limited agricultural data base of the previous work with the same objectives, namely, to determine the relationship between sensor parameters and performance. Included in the current study are such aspects as crop stress and analysis of results as a function of time of year of data collection. Additionally, this study addresses the question of performance versus field size.

The study's conclusions are derived from detailed analyses of simulated TM data, where the simulated data were based on previously collected aircraft MSS data. Aircraft scanners are characterized by narrow spectral bands, fine spatial resolution and high signal/noise, and as such their data is well suited to the simulation task. The MSS data for this study were gathered by the ERIM M-7 multispectral scanner during the 1971 Corn Blight Watch Experiment. Data from two locations in the state of Indiana, with one area covered at three times of year, were included in the study. The major ground covers in the area were corn, soybeans and trees.

Thematic Mapper data were simulated for many spatial resolutions, radiometric sensitivities, and sets of spectral bands, taking great care to accurately simulate the planned TM system. The simulated TM data were then processed using conventional machine classification techniques and the results were evaluated. Thus, the results of this study are mainly applicable to automatic information extraction techniques which are predominantly of the spectral rather than spatial discrimination type.

2. SPATIAL RESOLUTION

To study the effect of varying scanner spatial resolution, each of the four data sets, which exhibited a natural spatial resolution of about 10 meter ground patch size, were processed to create five new data sets of differing simulated spatial resolution: 30, 40, 50, 60 and 90 meters.* This simulation was accomplished by employing a spatial filter whose modulation transfer function (MTF) accurately matched that planned for the Thematic Mapper. The data were further modified by the addition of sufficient white noise to simulate the

*The 90 meter spatial resolution is equivalent to the resolution of the current Landsat scanners, using the rigorous definition of spatial resolution as the spatial frequency at the 50% response point on the system modulation transfer function.

nominal TM radiometric specification, generally, of 0.5 percent NE Δ p (noise equivalent reflectance difference). The simulation of the specified TM bands was carried out using the appropriate M-7 bands as shown in Table I.

These simulated data were classified using a maximum likelihood classifier and then analyzed by the criteria of acreage mensuration (proportion estimation), and field center classification.

To briefly summarize the results of the spatial resolution study, we first note that the principal measure of performance over an entire data set is the area mensuration (proportion estimation) accuracy over all pixels in the data set. Expected field center classification accuracy, in accord with theoretical considerations, was shown to be independent of scanner spatial resolution -- thus field center accuracy is not an adequate performance measure for system spatial resolution specification. The mensuration results for the four data sets, when examined as a function of spatial resolution, were best at 30 meters, inferior at 60 meters, and significantly worse at 90 meter resolution. Figure 1 presents these results using relative proportion estimation accuracy averaged over all classes as the measure. The trend to improved proportion estimation accuracy at finer spatial resolution depicted in Figure 1 is felt to be primarily because relatively fewer boundary pixels would occur for data at the finer spatial resolutions. It is important to note the consistent trends in these results over all the data sets studied. We further note that, for these parametric studies, only areas which yielded pure pixels at all resolutions were used for training since we did not want to confound differences due to spatial resolution with differences due to different training data.

A further consideration in choosing one spatial resolution over another is to understand what results would be for different areas in the world. The results reported above were for field size distributions that are representative of the U.S. corn belt. However, many other parts of the world -- Western Europe, India, parts of Asia, etc. -- have smaller average field sizes [5]. The impact of spatial resolution on overall mensuration accuracy for such areas was studied using simulation techniques which first constructed a series of appropriate scenes, where each scene was composed solely of fields of the same size and shape; then each scene was imaged, while varying spatial resolution as a parameter and expected mensuration accuracy was evaluated. A typical sample of these analyses, presented in Figure 2, is from a mid-August data set. Field sizes of 1-4 hectares are typical of Western Europe, India, etc, while the range 6-10 hectares is typical of the corn belt sites studied. As can be seen, significant reductions in accuracy occur with coarsening resolution for the smaller fields (1-4 hectares). In general, for such fields the loss of accuracy was 4-6% between 30 and 40 meter resolution; the decrease was 10-13% between 30 and 50 meter resolution. Even for 16 hectare fields (40 acres), a loss in mensuration accuracy of several percent is seen.

A final aspect of the spatial resolution study was an analysis of the TM thermal band. A majority of the study was carried out with all bands simulated as having equal spatial resolution, although in fact, TM was initially specified to have a thermal band with resolution on the order of 120 meters. A separate evaluation was therefore also made of the utility of a thermal band with 120 meter spatial resolution. This evaluation showed that in the typical corn belt scenes used here, almost no pure 120 meter pixels could be found for training purposes because of limitations in field size -- that is, in the thermal band most of the pixels were mixtures of different classes. The use of such a thermal band resulted in a serious reduction in mensuration accuracy. Thus it was that the major portion of this study was carried out using all bands of equal spatial resolution.

3. RADIOMETRIC SENSITIVITY

The second facet of the study involved empirical analysis of radiometric sensitivity, a parameter which may be very important. Evidence was obtained from simulations of field center classification accuracy for noise levels of 0.5s, 1.0s, 1.3s, 1.6s, 2s, 3s, 6s, 10s, and 20s where s is, by spectral band, the nominal specified noise equivalent reflectance/temperature difference ($NE\Delta\rho/\Delta T$). The nominal percent $NE\Delta\rho$ for the reflective region bands was 0.5%, except for the 1.55-1.75 μm band where it was 1.0%; the thermal band specification was for an $NE\Delta T$ of 0.5°K. Each of the radiometric sensitivity cases were analyzed for 30-meter and 40-meter spatial resolutions for both locations, three times of year at one location, and, furthermore, for two condition classes of corn in order to determine the effect of radiometric sensitivity on the discrimination between levels of corn blight. A range of discrimination difficulty was thus tested, including for these crop classes the more difficult early season and crop condition discriminations as well as the easier late season ones.

In the study of radiometric sensitivity, as expected, the results showed that classification accuracies decreased with increasing noise. An overall summary of the radiometric results is displayed in Figure 3, where it can be seen that for the Segment 204, July 12 (41M) data set, in which the major classes, corn and soybeans, are spectrally similar, the effect of decreased sensitivity is immediately evident. Although the results for the Segment 204, collected August 12 (43M), data set seem not to be so immediately affected, further examination of this data set showed that the recognition of corn, the key economic crop in the area, declined immediately with a small decrease in sensitivity. Furthermore, the correct detection of blight-stressed corn was seen, in Figure 4, to decrease significantly with immediate relaxation of sensitivity from the nominal point.

4. SPECTRAL BAND STUDY

The primary purpose of the spectral band study was to determine the adequacy of the specified TM bands for automatic discrimination of agricultural crops, as a function of the time of year and for the detection of non-systemic crop stress such as corn blight.

The bands considered in the study were the twelve M-7 bands, which cover the spectrum from 0.45 μm to 2.5 μm plus the thermal infrared. The algorithm used to find the optimum six bands tested all possible combinations of six bands. The optimum set was the one which minimized the measure used: average pairwise probability of misclassification averaged over all pairs of signatures of dissimilar classes. The signature set used for each of the four data sets was that extracted from the 30-meter spatial resolution data where training had been carried out using all fields in the scene with six or more pure pixels. Thus the selection of optimum bands was based on an exhaustive search algorithm using all the classes and spectral variation within each class for the scene.

As a comparison between the optimum set and the set of TM bands, the ERIM simulation classifier was run for both sets of bands. To determine the relative importance of each band in the optimum subset, rank orderings were also carried out. These results are summarized in Table II.

Several particular results were noted from the analyses carried out. The first is that the set of TM bands is as effective as the optimum set of M-7 bands for the times of year studied. Secondly, when analyses of spectral bands for detection of corn blight were carried out, it was seen that the 0.69-0.90 μm band was the most important band for discriminating between blight levels of corn. The only other band which also aided in this discrimination was the

1.0-1.4 μm band, which was seen to be highly correlated (redundant) with the above band for stress discrimination.

Thirdly, the thermal band was seen to be important early in the growing season. This result was consistent with experiments run during the Corn Blight Watch Experiment in 1971 [4]. In fact, the rank ordering of the set of TM bands for the mid-July data showed that the thermal band was second in importance -- only the green band (0.52-0.57 μm) was more important for this time period. However, one must bear in mind the spatial characteristic of the TM thermal band. While this study has used the same spatial resolution in all bands, the spatial resolution of the thermal band in the Thematic Mapper has been specified to be three to four times that of the other bands. The study carried out to determine the effects of coarser thermal resolution had shown a decrease in mensuration accuracy as a result. Here, the rank ordering of bands for this latter case ranked the larger IFOV thermal band fifth and, more importantly, predicted that its use would provide lower levels of recognition accuracy than would be obtained from a system exhibiting a finer resolution thermal band.

An additional point is that the two M-7 near-IR bands (1.0-1.4 and 2.0-2.6 μm) not included in the TM set were shown to be important. In particular, in ranking the set of optimum bands it was seen that the 1.0-1.4 μm band is second in importance of all bands for the mid-July (41M) data set.

5. CONCLUSIONS

We have presented the results of a study which provided additional empirical evidence for the definition of specifications for spacecraft multispectral scanners. The results were derived from analyses of simulated sensor data representative of U.S. Corn Belt crops as viewed at three different times in the growing season.

Conclusions Relating to Spatial Resolution and Radiometric Sensitivity

1. This study provides evidence that 30-meter or 40-meter spatial resolution, and a TM system radiometric sensitivity of half-percent reflectance would provide significantly better performance in automatic information extraction for agricultural crop survey applications (particularly corn and soybeans) than coarser resolution or less sensitive systems such as Landsat-1, -2, and -C.
2. Improvement in the area mensuration performance as a function of spatial resolution in the range of 30-90 meters was shown to be largely due to the lesser proportion of boundary elements (where classifier performance is low) at finer resolutions.
3. Improvement in performance with reduced noise levels in the range half-percent to one and a half-percent is more significant earlier in the growing season and with more difficult discriminations. Both mensuration and field center performance are affected.
4. Radiometric sensitivity is of great importance when defining future sensor systems, and may in fact be equal in importance with spatial resolution.
5. Thermal band resolution of 120 meters was shown to be detrimental to performance (when it would be used with other bands) in crop surveys compared to thermal band resolution equal to the other bands.

Conclusions Relating to the Spectral Bands

1. The six TM spectral bands selected are supported by this study as the best six bands for agricultural surveys of corn and soybeans, each band (including a fine resolution thermal band) being important at some time in the growing

season. The TM set gives essentially the same performance as the various sets of six optimum aircraft scanner bands appropriate to each time.

2. The 0.74-0.91 μm band is important for detection of crop stress conditions.

Additional Conclusion

1. Simulation of satellite or high altitude aircraft scanner performance using low altitude aircraft scanner data as an input is a powerful systems analysis technique.

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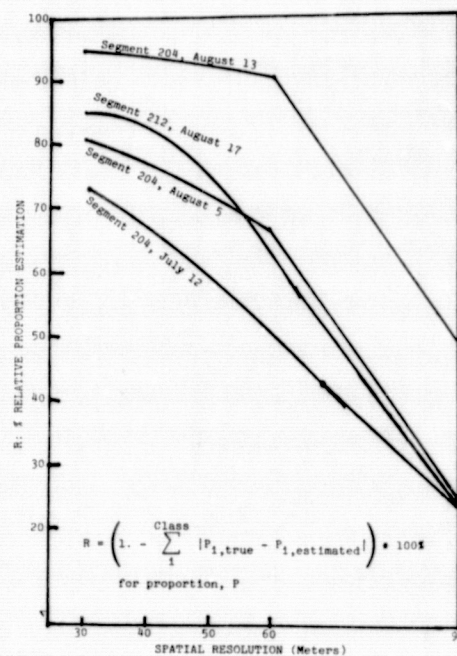


FIGURE 1. PROPORTION ESTIMATION WEIGHTED OVER ALL CLASSES

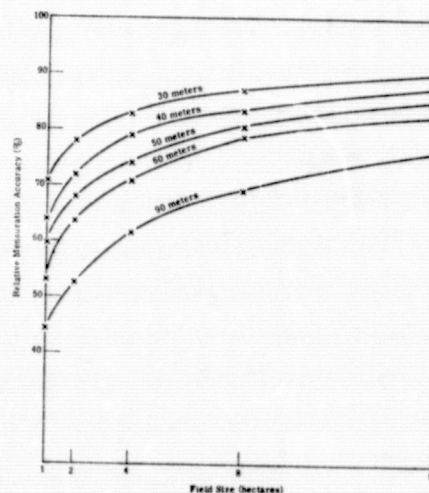


FIGURE 2. RELATIVE PROPORTION ESTIMATION (WEIGHTED OVER ALL CLASSES) AS A FUNCTION OF FIELD SIZE (2:1 ASPECT RATIO) WITH SENSOR SPATIAL RESOLUTION AS A PARAMETER. Data Set: Segment 208, August 13, 1971.

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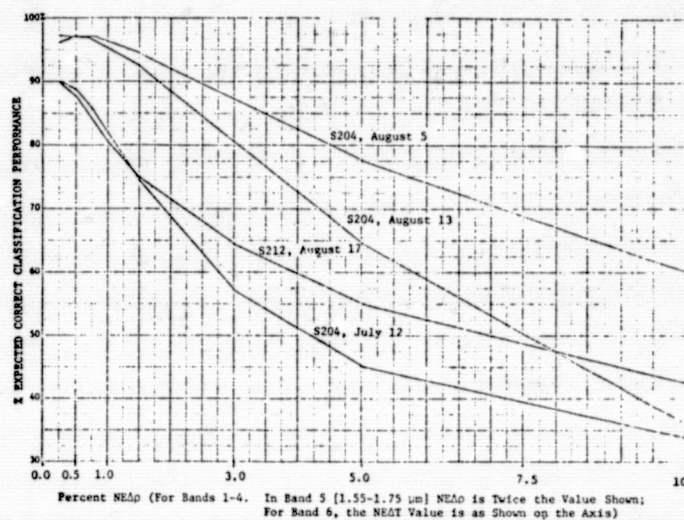


FIGURE 3. RADIOMETRIC SIMULATION -- 30 METER RESOLUTION -- PERFORMANCE OVER ALL CLASSES
(All Available Fields in Scene Utilized in Training Procedure)

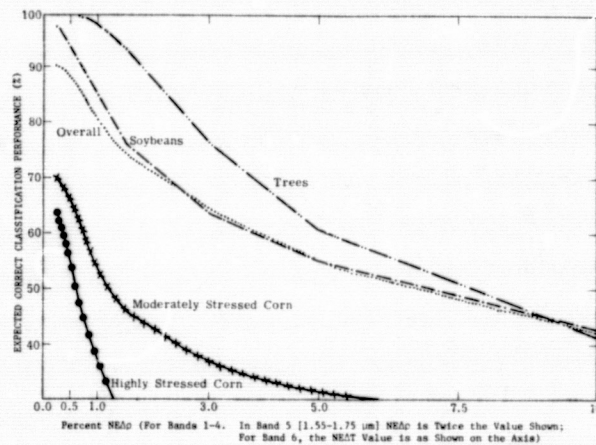


FIGURE 4. RADIOMETRIC SIMULATION -- 30 METER RESOLUTION -- PERFORMANCE BY CLASS
(SEGMENT S212, AUGUST 17)
(All Available Fields in Scene Utilized in Training Procedure)

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TABLE I. SIMULATION OF TM BANDS

RECOMMENDED TM BANDS	SIMULATED BANDS VIA M-7
0.45-0.52 μm	(0.46-0.49 μm) + (0.48-0.51 μm)
0.52-0.60 μm	(0.52-0.57 μm) + (0.54-0.60 μm)
0.63-0.69 μm	0.61-0.70 μm
0.74-0.91 μm	0.69-0.90 μm
1.55-1.75 μm	1.5-1.8 μm
10.4-12.5 μm	9.3-11.7 μm

TABLE II. OPTIMUM 6 BANDS FOR INDIANA CORN BELT DATA

DATA SET	OPTIMUM M-7 BANDS* (IN NUMERICAL ORDER)	OVERALL % CORRECT CLASSIFICATION OPTIMUM BANDS	OVERALL % CORRECT CLASSIFICATION FOR TM BANDS (2,4,7,8,10,12)**
Segment 204, July 12 (41M)	4,7,8,9,11,12	89.9	88.0
Segment 204, August 5 (42M)	2,4,7,8,11,12	92.6	92.6
Segment 204, August 13 (43M)	1,4,7,8,9,10	96.4	96.8
Segment 212, August 17 (43M)	2,4,8,9,10,11	93.5	93.0

* Band designations are: [6]

1 = .46-.49	4 = .52-.57	7 = .61-.70	10 = 1.5-1.8
2 = .48-.51	5 = .54-.60	8 = .69-.90	11 = 2.0-2.6
3 = .50-.54	6 = .58-.65	9 = 1.0-1.4	12 = 9.3-11.7

** TM Bands 1 and 2 were simulated by combining M-7 Bands 1 and 2, and 4 and 5 respectively.

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FURTHER TESTS OF THE SUITS REFLECTANCE MODEL

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ABSTRACT

Experiments performed by Allen and Richardson stacking cotton leaves in the port of a spectroradiometer indicate that single leaf reflectance ceases to vary with more than two leaves in the visible region and eight leaves in the infrared region. Chance and LeMaster have shown that the Suits spectral reflectance model predicts an asymptotic dependence of crop reflectance on leaf area index (LAI) with crop reflectance static for leaf area indices in excess of two in the visible region; and six in the infrared regions of the spectrum. These results are experimentally verified in the field for Milam and Penjamo spring wheat, and a theoretical relationship is discussed that relates crop reflectance at 650 nm to crop canopy LAI.

Experimental data are given that relate observer zenith angle to crop reflectance for wheat. The Suits reflectance model calculations for wheat fail to agree with this data.

1. INTRODUCTION

Chance and LeMaster [1] have shown that the Suits reflectance model predicts a relationship between crop reflectance and crop leaf area index (LAI). Unfortunately, little multitemporal data for crop reflectance could be found with which to test this relationship, so the authors embarked on an experimental program in the spring of 1977 to collect the necessary data for wheat. This paper represents preliminary findings of that study.

2. A REVIEW OF THE SUITS' MODEL

The Suits models for vegetative canopy reflectance result from a refinement of the model of Allen, Gayle, and Richardson [2] to give

- (a) deterministic formulations for all input parameters,
- (b) a method to calculate plant canopy reflectance as a function of sun and observer angles,
- (c) a multi-layer plant canopy.

A three compartment model is developed using upward, downward, and specular radiant flux by using energy conservation considerations. The upward diffuse, downward diffuse, and specular flux for a single wavelength λ are denoted, respectively, as $E_{\lambda}(+d,i,x)$, $E_{\lambda}(-d,i,x)$, and $E_{\lambda}(s,i,x)$ for radiation x units from the top of the canopy in the i -th layer, ($i=1,2,\dots,N$). Then one can write

$$\begin{aligned} \frac{dE_{\lambda}(+d,i,x)}{dx} &= -a_i E_{\lambda}(+d,i,x) + b_i E_{\lambda}(-d,i,x) + c_i E_{\lambda}(s,i,x) \\ \frac{dE_{\lambda}(-d,i,x)}{dx} &= a_i E_{\lambda}(-d,i,x) - b_i E_{\lambda}(+d,i,x) - c_i E_{\lambda}(s,i,x) \\ \frac{dE_{\lambda}(s,i,x)}{dx} &= k_i E_{\lambda}(s,i,x). \end{aligned} \tag{1}$$

The five parameters a_i , b_i , c_i , c'_i , and k_i are calculated as functions of the sun angle, leaf geometry, and optical properties for leaves taken from the i -th layer [3].

A solution of system (1) is found by using a combination of initial and boundary conditions. Total crop radiance in the direction of an observer is then found by integration.

The resulting model for crop reflectance shows fair agreement with wheat reflectance data collected by the authors from 0.50 μ m to 1.10 μ m, and good agreement with wheat reflectance data collected by Kanemasu for Scout wheat [4] as shown by Chance in [5]. On the other hand, model calculations and experimental data taken from a wheat field failed to show agreement for the change in crop reflectance as a function of sun angle [1].

3. A DISCUSSION OF THE MODEL DEPTH

The single layer Suits model indicates that crop reflectance changes as a function of crop LAI. In the infrared region, crop reflectance increases as LAI increases, and approaches a limiting reflectance, R_∞ . In the visible region, crop reflectance decreases as LAI increases, and again approaches an asymptotic reflectance. To determine practical limits at which reflectance ceases to vary as a function of LAI, the LAI was increased in the model by varying only the canopy depth x , and finding the smallest depth x , called the model depth, at which crop reflectance is within 5% of infinite reflectance. Figure 1 is a graph of the relationship between crop reflectance calculations and canopy depth for (a) 850 nm and (b) 650 nm using cotton plant canopy parameters. Figure 2 is a plot of model depth as a function of wavelength for cotton canopy parameters. The Suits model calculations predict limiting crop reflectances at 650 nm and 850 nm for crop LAI greater than 2.13 and 6.11 respectively. Model depth for a canopy has a physical interpretation. Canopy depths in excess of the model depth cause only minor changes in crop reflectance and are a measure of the upper limit to which cumulative leaf area index affects crop reflectance. Allen and Richardson [5] have observed phenomena analogous to model depth by stacking cotton leaves over the port of a spectrophotometer.

4. A RELATIONSHIP BETWEEN LAI AND CROP REFLECTANCE

In what follows, it is necessary to refer to the equations found in Suits [3]. Equations (18) and (20) of [3] give single layer crop reflectance as a function of the various parameters and is, for all practical purposes, unwieldy to use. These equations can be approximated in the chlorophyll absorption region of the spectrum by (23) in [3], that is,

$$\pi L_\lambda / E_\lambda(s, 0) = \frac{W_1}{K_1 + k_1} \left[1 - \exp[x_1(K_1 + k_1)] \right] + \exp[K_1 x_1 + k_1 x_1] \rho(\text{soil}). \quad (2)$$

This equation can be simplified a great deal by viewing the crop from zenith for a fixed sun angle. $K_1 x_1 + k_1 x_1$ becomes proportional to the leaf area index of the crop, so

$$K_1 x_1 + k_1 x_1 = -an$$

where n is the crop leaf area index and a is a constant to be determined. Further,

$$\lim_{x_1 \rightarrow -\infty} \left[\frac{\pi L_x}{E_\lambda(s, 0)} \right] = \frac{W_1}{K_1 + k_1} = R_\infty$$

where R_∞ is the infinite crop reflectance.

Thus, if one denotes

$$\frac{\pi L_{\lambda}}{E_{\lambda}(s,0)} = R(n)$$

and $\rho(\text{soil}) = R_s$, then the Suits approximation (2) can be rewritten as

$$R(n) = R_{\infty}(1 - e^{-an}) + R_s(e^{-an}). \quad (3)$$

Equation (3) expresses the crop reflectance $R(n)$ as a mixture of the bare soil reflectance and the infinite crop reflectance, since

$$(1 - e^{-an}) + e^{-an} = 1.$$

This relation gives crop reflectances near to the reflectance of bare soil for low LAI and crop reflectances near to the infinite reflectance for large LAI. Equation (3) can be solved for the leaf area index n to give

$$n = \frac{1}{a} \ln \left[\frac{R_{\infty} - R_s}{R(n) - R_{\infty}} \right] \quad (4)$$

an equation that can be utilized once R_{∞} and the proportionality constant a are determined.

R_{∞} can be determined experimentally by a method analogous to the leaf stacking technique devised by Allen and Richardson. A portion of the plants in the canopy are uprooted and stacked in a dense pile (large LAI) over a bare soil background. The infinite reflectance R_{∞} can thus be determined by measuring the reflectance of this plant stack. The constant a is determined by use of the Suits model. Using the Suits model and experimental parameter for cotton it was found that at 650 nm

$$1.05 R_{\infty} = R(n) \quad \text{when } n = 2.13.$$

While this condition is determined by use of cotton parameters in the Suits model, it has been found by use of wheat parameters in the Suits model that reflectance in the visible regions ceases to vary at an LAI of three [5]. In any case, experimentation with the plant stack mentioned above can accurately determine the value of the constant a . Once R_{∞} and a are determined (4) can be used for a priori estimates of crop LAI. This technique is currently being evaluated experimentally by the authors, and is felt to be a viable alternative to the standard techniques of plant sampling to determine LAI. Crop reflectance taken from the field either in a single determination by aircraft or satellite or in multiple determinations with a hand held radiometer, enables one to non-destructively sample the crop condition throughout the entire field, thereby reducing the variability caused by the traditional small area determinations of LAI.

It is of interest to note that (3) can be rewritten as

$$R(n) = (R_{\infty} - R_s) e^{-an} + R_{\infty}$$

from which it can be seen that if the crop infinite reflectance equals the bare soil reflectance, $R(n)$ does not vary as a function of crop LAI but equals R_{∞} for all n . In this case, the model depth is zero, which occurs as seen in Figure 2 at about 680 nm.

5. EXPERIMENTAL RESULTS FOR LAI

Two irrigated test plots at the USDA, ARS Experimental Farm in the Lower Rio Grande Valley of Texas were seeded at 60 kg/hectare with Milam and at 90 kg/hectare with Penjamo wheat on November 30 and December 6, 1976, respectively.

Weekly determinations were made of the following crop parameters: LAI, single leaf reflectance and transmittance, crop spectral reflectance, Suits model parameters, directional reflectance at 550 nm and 850 nm, and bare soil spectral reflectance. Results shown here are a result of this study.

Leaf area index values were found weekly by removing plants from a measured distance along at least two rows and calculating the ratio of the total leaf area (found by direct measurement on a Hayashi Denko optical planimeter) to the ground area of the plants. The Penjamo LAI values range to a high of about 6 while the Milam values were a maximum of 9. The larger value for Milam was a result of the greater tillering of the Milam. LAI for both crops seem quite high, but are reasonable from consideration of the mild wet winter in south Texas in 1976-77 and the high seeding rates used in this experiment.

Relative reflectance values were determined in 50 nm increments using a wedge-filter type radiometer (ISCO Model SR) equipped with a 1.8m fiber optics probe. The radiometer field of view to half maximum was 13°; the spectral bandwidth was 15 nm in the visible and 30 nm in the ir. Reflectances were determined from a 5.7 meter tower relative to a standard panel coated with barium sulfate-based paint (Eastman Kodak White Reflectance Coating, #6080).

It was previously observed by the authors [1] that the Suits model for a single-layer wheat canopy predicts an exponential dependence of reflectance on LAI as shown in Fig. 1. Experimental data is presented in Fig. 3 for Milam 650 nm reflectance versus leaf area index and 850 nm reflectance versus leaf area index is shown in Fig. 4. The general trends at both wavelengths are in agreement with the Suits model. The 650 nm reflectance shows a clear exponential behavior, approaching an infinite reflectance of about 0.03. The 850 nm reflectance values approach a value of about 0.55 but do not appear to have a clear exponential behavior. The decrease of 650 nm reflectance with increasing LAI is due to the lower value of the single leaf reflectance at that wavelength compared to the soil. Increasing the LAI decreases the reflectance by covering the soil. Likewise the increase in reflectance at 850 nm with LAI is caused by single leaf reflectance values being greater than the soil background. An additional factor that can account for the dissimilarity in the rates at which the reflectance curves of Fig. 3 and Fig. 4 approach their asymptotes is that leaves at 650 nm are highly absorbing (~80% of radiation striking them) and at 850 nm the absorptance is low (~5%).

The data of Fig. 3 for 650 nm show less scatter than the data of Fig. 4 for large LAI. The relatively small scatter in Fig. 3 is due to the high absorptance of all plant components causing an insensitivity of the reflectance to LAI measurements greater than 3. The fact that all reflective components of the canopy have about the same optical properties at 650 nm also means the canopy reflectance does not change as stems and heads develop during the latter part of the growing season. The 850 nm reflectance in Fig. 4 shows scatter due to errors in LAI measurements because of the sensitivity of crop reflectance to LAI values less than 7. The 850 nm reflectance of single leaves is considerably lower than for stems and heads [1]. The crop reflectance will therefore show a sensitivity to stem and head development at 850 nm as the crop matures. The data of Fig. 4 shows a clear exponential rise of reflectance with LAI for LAI values up to 6 similar to the one layer Suits model of Fig. 1. The data indicate that stem and head development became prominent in the canopy for LAI greater than 7, thereby accounting for the further increase in reflectance for LAI greater than 6.

6. EXPERIMENTAL RESULTS FOR OBSERVER ANGLE EFFECTS

The dependence of reflectance on sun angle for Penjamo wheat was presented in [1]. The experimental data at 550 and 850 nm showed that crop reflectance for wheat increased with sun zenith angle while the Suits model predicted that crop reflectance decreases. The dependence of the reflectance of

Penjamo wheat on observer angle shows similar behavior - an increase in reflectance with observer zenith angle for fixed sun angle. This is shown in Fig. 5 for 850 nm and Fig. 6 for 550 nm. The Suits model calculations shown in these figures predict a decrease in reflectance with increasing observer zenith angles which does not agree with experimental observations.

The failure of the Suits reflectance model to correctly predict bidirectional reflectance trends for sun and observer angles can be attributed to two sources.

- (a) Those parameters in the Suits model that contain observer or sun angle dependencies. These parameters need to be modified.
- (b) The Suits model is based on the assumption that leaves are lambertian reflectors. Breece and Holmes [6] have shown that with specular irradiance leaves are non-lambertian reflectors, a fact that cannot be ignored on the top surface of a plant canopy.

7. CONCLUSIONS

The Suits model shows good qualitative agreement with experimental data on reflectance versus LAI and suggests a technique for the remote sensing of leaf area index at 650 nm. The sun angle and observer angle dependence of the reflectance of wheat is not correctly accounted for by the Suits model and thus the model needs modification. The model is in best agreement with experimental data at small sun and observer zenith angles, and at these angles reasonable to good spectral reflectance calculations have been obtained.

8. ACKNOWLEDGEMENTS

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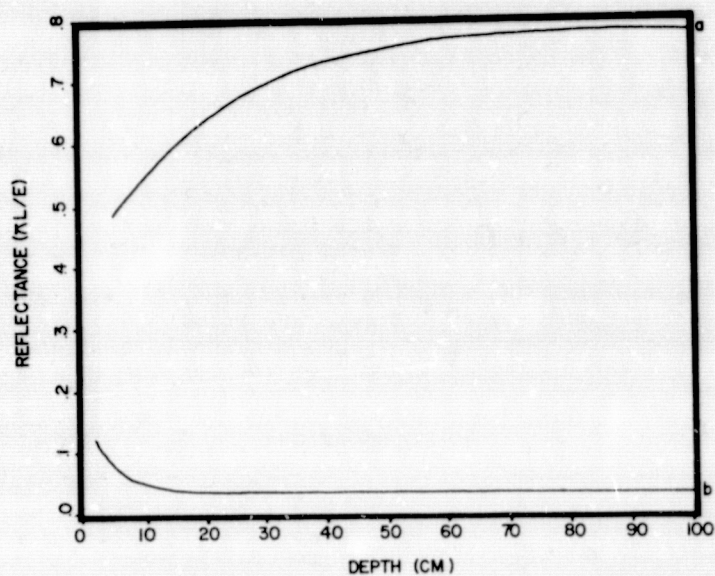


Figure 1. The relation between canopy depth and reflectance ($\pi L/E$) calculated from the Suits model at (a) 850 nm in the upper curve and (b) 650 nm in the lower curve for a cotton canopy. The horizontal asymptotes are the infinite canopy reflectance.

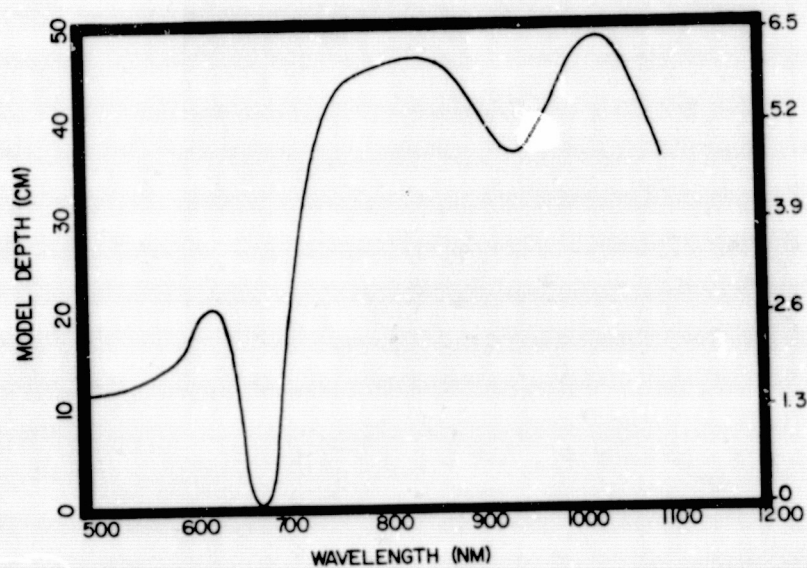


Figure 2. The model depth for a cotton canopy as a function of the wavelength. The scale on the right is LAI.

MILAM 650NM

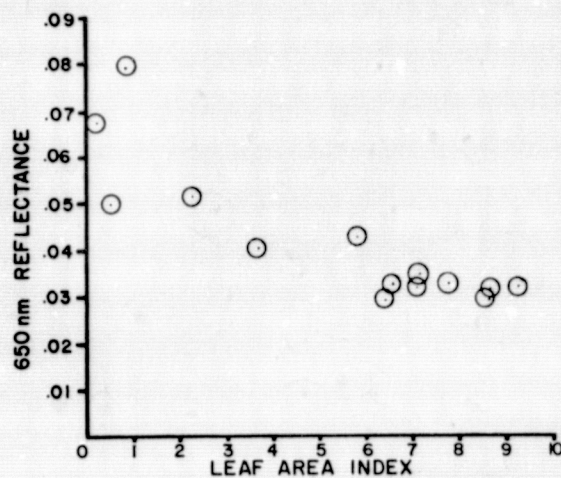


Figure 3. Milam wheat reflectance at 650 nm as a function of LAI. Values are weekly measurements from emergence through soft dough stage, Dec. 7, 1976, through March 14, 1977. Sun angles and sky conditions were variable.

MILAM 850NM

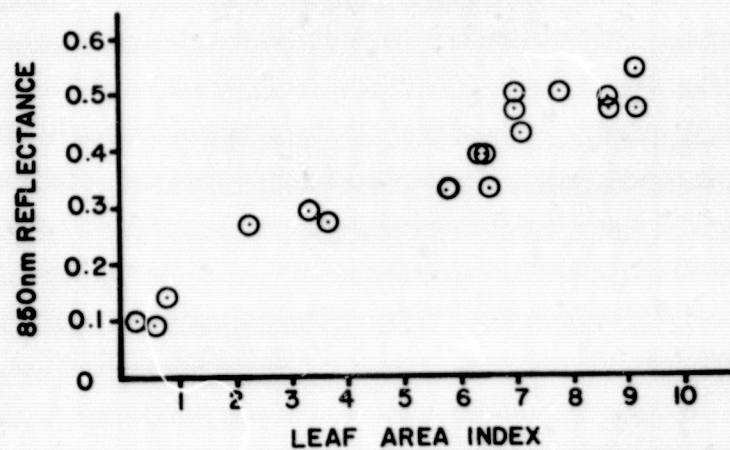


Figure 4. Milam reflectance at 850 nm as a function of LAI. Details the same as Fig. 3.

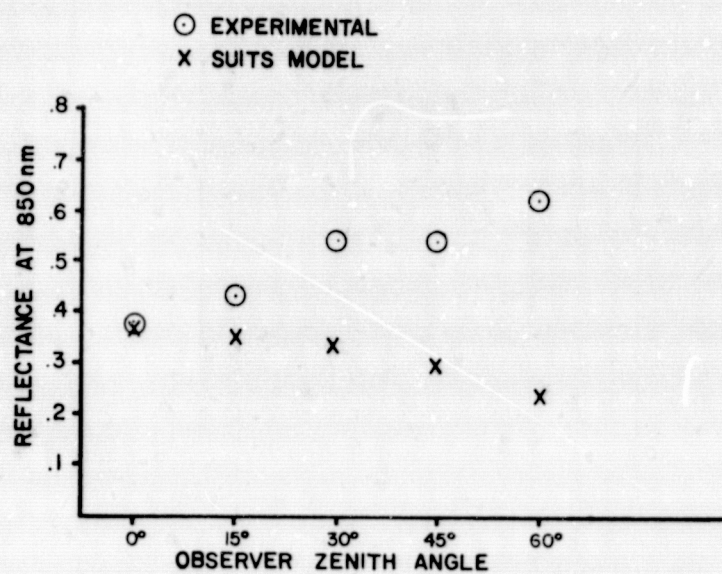


Figure 5. Penjamo wheat reflectance at 850 nm as a function of observer zenith angle. The LAI was 4.1 and the sun zenith angle was 52° at 3:25 pm; the observer direction was toward the west.

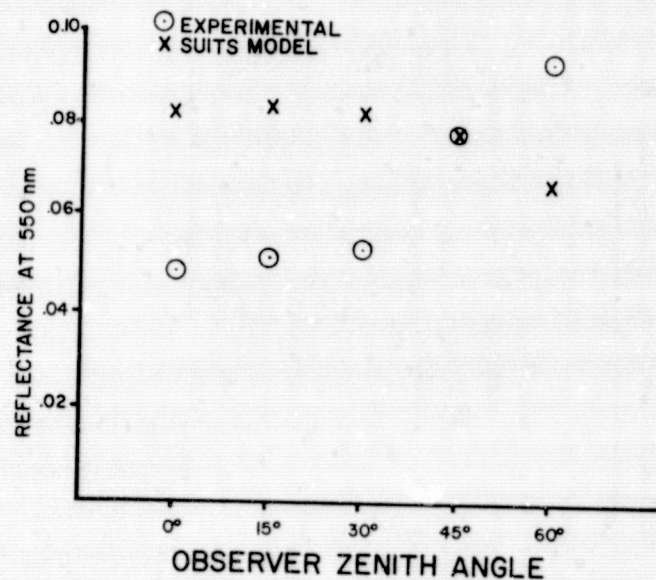


Figure 6. Penjamo wheat reflectance at 550 nm as a function of observer zenith angle. Other parameters the same as Fig. 5.

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ESTIMATION OF OLD FIELD ECOSYSTEM BIOMASS

USING LOW ALTITUDE IMAGERY*

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ABSTRACT

Color-infrared photography was used to evaluate the biomass of experimental plots in an old-field ecosystem that was treated with different levels of waste water from a sewage treatment facility. Cibachrome prints at a scale of approximately 1:1,600 produced from 35 mm color infrared slides were used to analyse density patterns using prepared tonal density scales and multicell grids registered to ground panels shown on the photograph. Correlation analyses between tonal density and vegetation biomass obtained from ground samples and harvests were carried out. Correlations between mean tonal density and harvest biomass data gave consistently high coefficients ranging from 0.530 to 0.896 at the 0.001 significance level. Corresponding multiple regression analysis resulted in higher correlation coefficients. The results of this study indicate that aerial infrared photography can be used to estimate standing crop biomass on waste water irrigated old field ecosystems. Combined with minimal ground truth data, this technique could enable managers of wastewater irrigation projects to precisely time harvest of such systems for maximal removal of nutrients in harvested biomass.

INTRODUCTION

Farm lands on marginal soils have been abandoned over much of the United States. These relatively inexpensive and underutilized lands represent ideal resources for renovation of municipal wastewater. This wastewater renovation relies on the ability of soils to sorb phosphorus and heavy metals and the ability of plants to remove nitrogen by incorporation in their biomass. The uptake of nitrogen by plants is essential since microbial conversion of organic and ammonium nitrogen to the easily leached nitrate-nitrogen form occurs rapidly under the rather ideal, high moisture and carbon conditions associated with wastewater irrigation. Improperly managed systems can result in NO₃-N leachates that exceed the generally accepted drinking water standard of 10 mg/l resulting in groundwater contamination. Thus, uptake of N in vegetation and its subsequent harvest and removal from the site is an integral part of a well managed land irrigation wastewater system.

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The timing of harvest is also critical since nitrogen content of plant tissues declines as growth slows. The ideal harvest combines maximal biomass removal with highest possible N content of plant tissue (1). Such a harvest results in maximal removal of N from the site and in the highest quality compost or feed for use elsewhere. Remote sensing technology can potentially be a valuable aid in monitoring biomass accumulation when combined with a minimal amount of ground truth data in the form of chemical analysis of plant tissue and a limited number of on-site plant biomass estimates. This calibrated, remotely sensed data would be a valuable aid in management of such systems.

There are several studies which indicate that the spectral reflectance characteristics of a plant canopy can be used to estimate standing plant biomass (ref. 2-4, 6-10). These studies have shown that the magnitudes of green, red and near infrared reflectance and/or reflectance ratio combinations involving these wavelengths can be used for standing plant biomass determinations under some conditions. More sophisticated approaches, using mathematical spectral reflectance models, have increased our understanding of the nature of plant canopy light reflectance (ref. 2, 3, 6, 7, 10). Infrared color photographic techniques utilize reflected light in the green, red and near infrared wavelengths, and there is evidence that these techniques can be used to estimate relative standing crop biomass (ref. 6, 8) as well as crop vigor (ref. 8).

The Institute of Water Research at Michigan State University, East Lansing, is studying the feasibility of wastewater recycling by abandoned old field ecosystems. The ecosystems being studied consist of a diverse community of grasses and weeds with quackgrass (*Agropyron repens*) and goldenrod (*Solidago sp.*) being the predominant species. Biomass determinations of grass communities using spectral reflectance analyses are generally more successful than for other plant communities (ref. 4). The use of infrared aerial photography for biomass determination of mixed grass and weed canopies typical of successional old field ecosystems has not been attempted previously. The purpose of this study was to demonstrate the feasibility of using aerial infrared photography for biomass determination in old field ecosystems used for renovation of municipal wastewater.

MATERIALS AND METHODS

Field Plots--The experimental old field ecosystem was divided into four blocks of six plots each in two rows of three. Each plot was 24.4 m wide and 27.4 m long. Two adjacent experimental blocks with 6 treatments were set up in an unsprayed area to serve as non-irrigated controls. Within each irrigated block, three plots received 5 cm/week wastewater with the remaining three plots receiving 10 cm/week of wastewater. Within each irrigation treatment, one plot received no harvest, one plot was harvested in June, and one plot was harvested in both June and September. Harvest treatments were randomly assigned within blocks. Thus, each treatment was duplicated in each of 4 experimental blocks with 4 plots receiving 5 cm/week wastewater and no harvest, 4 plots receiving 5 cm/week wastewater and a June-only harvest, and 4 plots receiving 5 cm/week wastewater and a June and September harvest. These harvest treatments were repeated for the 10 cm/week wastewater treatment. The non-irrigated control plots were randomly divided on a block by block basis into 4 plots with no harvest, 4 plots with a June-only harvest, and 4 with a June and September harvest.

Vegetation samples were taken at two to four week intervals with four 0.25 m² samples randomly taken within each of the 36 plots. Vegetation was clipped at ground level, stored in plastic bags under refrigeration, sorted to species, dried, weighed, ground in a Wiley mill, and subsampled on a species basis for nutrient analyses. Dry weight biomass accumulation was calculated from these random quadrant samples.

The harvest plots were harvested with a silage chopper on June 15, 1976. Prior to harvest, three subsamples consisting of 9.1 m x 0.76 m strips were taken from both harvest and non-harvest plots using a small tractor and hand

equipment. All vegetation on each strip was weighed for wet weight determination of harvest biomass. Subsamples were dried for moisture determination so that dry weight biomass could be calculated. The June and September harvest plots were harvested again on September 3, 1976 and harvest subsamples were taken from all plots using the same technique.

PHOTOGRAPHIC ANALYSIS

The plots were photographed from a light plane on four different occasions from May to September in the summer of 1976, nearly concurrent with field sample or harvest dates. The photographs were taken using a 35 mm Nikon camera at f5.6 and 1/500th second. Kodak Extachrome infrared film was used with a Wratten 12 filter. Two cibachrome prints (20 x 26 cm) at a scale of approximately 1:1,600, were produced from a selected 35 mm color-infrared slide of each flight.

The last three imageries were fairly similar in tone to each other, being uniformly dark reddish-purple, particularly over the treatment blocks. The first imagery, taken in mid-May 1976, was light orange-pink. The vegetation cover was not yet full and soil was visible, appearing bluish in tone. In general the control blocks were more open than the treatment blocks in all four photographs. Their tonal appearances were also generally darker due to more soil being visible, although this contrast was less in the May imagery than in the later imagery.

An eight and a five-level tonal density scale was established for the May imagery while only a five-level scale was set for the other three imageries. "Standard" tonal chips were then prepared from one of the prints of each set.

Transparent multicell grids of variable densities were produced in order to determine the optimum grid density for photo interpretation.

With these grids registered to ground panels shown on the photographs and using the tonal density scales, the tonal density value of each cell of the grid is recorded, thus giving a series of tonal values for each plot. This was repeated with different grid densities. In order to reduce bias, interpretation with each set of grids was carried out on different days, and in order to retain continuity and uniformity, interpretation for each grid size was done on one day.

ANALYSIS AND RESULTS

Simple Correlation Analysis--A mean tonal value was calculated for each photo plot from the tonal values of each grid cell. Pearson correlation analysis was carried out between mean tonal density and plot biomass. Table 1 summarizes the results of the analysis using the 5-19-76 and 6-11-76 imagery with different grid sizes and tonal density levels.

Table 1 shows that correlations between mean tonal density and sample biomass were consistently low and statistically not significant. Correlation coefficients ranged from as low as 0.001 to as high as 0.41. Correlations with the 6-5-76 sample data were generally better than the 5-22-76 sample data using the 5-19-76 imagery. This tends to indicate that the imagery has a better capability for predicting older vegetation biomass than that of younger vegetation biomass. In other words, the imagery tends to reflect future conditions of the ecosystem better than present conditions.

Correlations of mean tonal density and harvest data were consistently better in all cases and were also statistically significant at a minimum of a 5% significance level. Moreover, correlation coefficients with wet weight biomass were also consistently higher than with dry weight biomass. Whereas correlations with dry weight biomass ranged from 0.53 to 0.69, correlations with wet

weight biomass ranged from 0.57 to 0.86. This reflects that the reflectance of the vegetation as recorded by the infrared imagery is an indication of the whole living biomass of the plants including water, and not just the dry organic matter.

There appears to be no relationship between grid density and correlation coefficient. Even eyeballing the whole plot, without using any grid gave comparable correlation coefficients. There also appears to be no consistent difference between using a five level and an eight level tonal density scale. In view of these results, it was concluded that a five level tonal density scale is better as it would be easier to apply. A 4 x 5 (20 cell) grid is recommended as twenty readings will offset any random errors in tonal estimation and would also allow analysis by multiple regression techniques.

Multiple Regression Analysis--The multicell interpretation of each plot allows the use of multiple regression techniques to analyze the relationship between tonal density and biomass. A multiple regression analysis is a more valid analytical procedure with this data as the tonal density levels are ordinal data. The use of a mean of an ordinal data for correlation analysis is statistically invalid. The multiple regression technique overcomes this limitation as it does not use the tonal density level values but uses the frequencies of each tonal density level per plot as the independent variables.

The use of multiple regression is also hypothetically justified as the total biomass of the plot can be visualized as the weighted sum of the biomass represented by each tonal level. Thus the frequencies of each tonal level will more truly reflect any relationship between biomass and tonal density.

Table 2 gives a summary of the multiple regression coefficients for the 5-19-76 and 6-11-76 imagery using different grid densities and tonal density levels. In order to overcome the linear relationship between the independent variables, one independent variable is not used in the regression model.

A comparison between Tables 1 and 2 will show that the multiple regression coefficients were generally better than the corresponding simple correlation coefficients. Multiple regression coefficients with wet biomass ranged from 0.6 to 0.9 and were all significant at the 1% level. The higher regression coefficients mean that a greater part of the variability of the dependent variable can be explained using the multiple regression analysis than with a simple regression analysis. However, although the multiple regression technique gives higher regression coefficients, there are more parameters to be estimated in the multiple regression than in a simple regression. Thus caution must be exercised before one chooses the multiple regression model over the simple regression model as a predictor model (Draper and Smith, ref. 5). Therefore each regression model must be analysed before a choice is made. However, the multiple regression analysis is statistically valid and the use of a multicell grid in the interpretation offers the opportunity of overcoming the invalid use of ordinal data in regression analysis.

Analysis of 6-29-76 and 9-2-76 Imagery--After the 24 treatment plots were harvested on 6-15-76, the unharvested plots were re-photographed on 6-29-76, while the regrowth on the treatment plots were re-harvested and re-photographed on 9-2-76. Interpretation was done using a 20 cell (4 x 5) grid with a five tonal density level for the control (6-29-76 imagery) and treatment plots (9-2-76 imagery).

The results of a simple and multiple regression analysis is given in Table 3.

TABLE 3: REGRESSION COEFFICIENTS OBTAINED WITH 6-29-76 and 9-2-76 IMAGERY

Photo Date	Simple Correlation Coeff.			Multiple Regression Coeff.		
	6-25-76 Sample	9-2-76 Harvest (Dry)	9-2-76 Harvest (Wet)	6-25-76 Sample	9-2-76 Harvest (Dry)	9-2-76 Harvest (Wet)
6-29-76	.328	.55*	.65*	.70	.72	.80*
9-2-76	---	.90**	.88*	--	.91**	.89**

* Significant at 5% level.

**Significant at 1% level.

The above results reflect similar relationships as obtained earlier, in spite of the lower number of cases. Correlations with harvest data were higher than the simple correlation coefficients but the lack of statistical significance is due to the low degrees of freedom (only 12 cases). In spite of only 24 cases for the 9-2-76 imagery, both the simple and multiple regressions gave highly significant results, but the correlation with dry weight biomass is slightly better than wet weight biomass, which is contrary to the general tendencies shown earlier.

CONCLUSIONS

The results of this study show that low altitude 35 mm color infrared imagery taken as early as one month before harvest can be used to estimate the relative standing biomass of an old field ecosystem irrigated with wastewater. Correlations of mean tonal density values and quadrant sample dry weight biomass data were low and statistically not significant, as was also the case between early sample biomass data and final harvest biomass data. However correlations with wet weight biomass data were better than with dry weight biomass data in nearly all cases. The use of a five level tonal density scale gave similar results as an eight level tonal scale. The use of different grid densities did not appear to affect the correlations, as even eyeballing the tonal density level of the whole plot gave comparable results.

The use of a multicell grid however, offers the use of multiple regression analysis of the data. The use of the mean tonal density level value in a correlation analysis is statistically invalid as the tonal density levels are ordinal data. Use of multiple regressions overcomes this important statistical limitation as the analysis uses the frequencies of grid cells with each tonal density level in each plot. Multiple regression analysis also results in higher regression coefficients in all cases.

It should be reemphasized that the wastewater irrigated old field ecosystem had quackgrass and goldenrod as the dominant plant species. There are reports in the literature of problems in correlation reflectance data with standing plant biomass when the plant communities are not dominated by grass species. In the case of a wastewater irrigated ecosystem, however, quackgrass often becomes more dominant the longer the system is under irrigation. Thus, our ability to estimate biomass should increase each year the system is under irrigation.

The results of this study indicate that aerial infrared photography can be used to estimate standing crop biomass on wastewater irrigated old field ecosystems. This technique, when combined with minimal ground truth data, should allow managers of wastewater irrigation projects to precisely time harvest of such systems for maximal removal of nutrients in harvested biomass.

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TABLE 1: SUMMARIZED CORRELATION COEFFICIENTS FOR ANALYSIS
OF 5-19-76 AND 6-11-76 IMAGERY

Photo Date	# of Levels	Grid Size	FIELD DATA DATES			
			5-22-76 Sample	6-5-76 Sample	6-15-76 Harvest (Dry)	6-15-76 Harvest (Wet)
1. 5-19-76	5	(6x7) grid	0.0341	0.2018	0.6086**	0.8196**
2. 5-19-76	5	(5x6) grid	0.1418	0.2724	0.6108**	0.7352**
3. 5-19-76	5	(4x5) grid	0.0479	0.3973*	0.6787**	0.8403**
4. 5-19-76	5	(3x4) grid	0.0627	0.3292*	0.6483**	0.7932**
5. 5-19-76	8	(6x7) grid	0.0111	0.3380*	0.6583*	0.8583*
6. 5-19-76	8	(5x6) grid	0.0011	0.4135*	0.6221**	0.8431**
7. 5-19-76	8	(4x5) grid	0.0288	0.3101*	0.6407**	0.8221**
8. 5-19-76	8	(3x4) grid	0.0951	0.3567*	0.6644**	0.7636**
9. 6-11-76	5	(6x7) grid	--	--	0.6646**	0.8621**
10. 6-11-76	5	(5x6) grid	--	--	0.6724**	0.8603**
11. 6-11-76	5	(4x5) grid	--	--	0.6894**	0.8612**
12. 5-19-76	5	EYEBALL	0.0350	0.3681*	0.5339**	0.7718**
13. 6-11-76	5	EYEBALL	--	--	0.6913**	0.8575**

* Significant at 5% level.

** Significant at 1% level.

Note: Number of cases = 36.

TABLE 2: SUMMARIZED MULTIPLE REGRESSION COEFFICIENTS
FOR ANALYSIS OF 5-19-76 AND 6-11-76 IMAGERY

Photo date	# of Levels	Grid Size	GROUND BIOMASS DATA			
			5-22-76 Sample	6-5-76 Sample	6-15-76 Harvest (Dry)	6-15-76 Harvest (Wet)
1. 5-19-76	5	6x7	.487*	.329	.722**	.856**
2. 5-19-76	5	5x6	.557*	.330	.662*	.790**
3. 5-19-76	5	4x5	.131	.451	.741**	.861**
4. 5-19-76	5	3x4	.388	.468*	.731*	.812**
5. 5-19-76	8	6x7	.437	.395	.708**	.895**
6. 5-19-76	8	5x6	.552*	.603*	.752**	.861**
7. 5-19-76	8	4x5	.414	.535	.667**	.847**
8. 5-19-76	8	3x4	.391	.508	.721**	.847**
9. 6-11-76	5	6x7	--	--	.715**	.876**
10. 6-11-76	5	5x6	--	--	.725**	.893**
11. 6-11-76	5	4x5	--	--	.697**	.861**

* Significant at 5% level.

** Significant at 1% level.

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THE EFFECT OF SOIL WATER DEFICIT
ON THE REFLECTANCE OF CONIFER SEEDLING CANOPIES

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ABSTRACT

The effects of soil water deficit on spruce and pine seedling canopy reflectance, needle reflectance and transmittance, and canopy density were measured in a greenhouse with a diffuse source of radiant flux. A potential for early or pre-visual detection of plant water stress was not supported by these measurements made at visible, and reflected infrared wavelengths to 1950 nm. Needles were found to transmit approximately thirty percent of the radiant flux incident on them at 780 nm, ten percent at 700 nm, and were found to be opaque at 450, 550, 600 and 650 nm.

1. PURPOSE AND JUSTIFICATION

The purpose of this experiment was to measure the variation in conifer seedling canopy reflectance, needle hemispherical reflectance and transmittance, and needle density and orientation associated with differing levels of soil water potential.

High altitude images of dense conifer plantations often lack significant relief displacement, pattern, texture, and size and shape characteristics of the tree crowns which have been recognized as necessary image qualities for analyzing forest ecosystems (Haack, 1962 and Wilson, 1967). Therefore, the value of remote sensing for forest land management depends increasingly on the information obtainable from radiance data alone as platform altitude becomes higher. An understanding of the causes of observed variations in forest canopy reflectance is necessary as a first step towards the reliable extraction of forest parameters from high altitude images. Tissue necrosis associated with severe and prolonged periods of soil water deficit has been observed to modify needle reflectance and thereby, canopy reflectance very significantly (Heller, 1971). Symptoms of attack by many forest insects or pathogens are similar to those induced by moisture stress (Weber and Olson, 1967 and Talboys, 1968) and such attacks may also alter canopy reflectance. Potted seedlings were used to simulate a forest canopy and measure the effects of soil water deficit on canopy reflectance during a prolonged period of stress. The plant water stress induced by a limited watering of the soil contained in the seedling pots was planned to simulate the effects often induced by forest insects or pathogens as well as those induced by soil water deficit occurring in the natural environment.

*The author wishes to acknowledge financial support from the University of Michigan for this project.

The importance of the angular relationship between the source of electromagnetic radiation, the object scene and the sensor has been known for many years (Spurr, 1948 and Olson, 1962). In this experiment, reflectance measurements were made only when the entire hemisphere of the sky provided a diffuse source of radiant flux passing through the roof of the greenhouse. Azimuth and solar zenith angle effects were eliminated under the diffuse source thereby reducing data collection requirements and precluding any study of the interaction between changes in canopy reflectance caused by solar zenith and azimuth angle variation and changes caused by water stress. The canopy reflectance, measured in this experiment, was thought to be sensitive to any changes in needle reflectance and transmittance and to changes in percent vegetation cover brought about by increasing soil water deficit.

2. EXPERIMENTAL DESIGN

Red pine (*Pinus resinosa* Ait.) and white spruce (*Picea canadensis* Mill.) seedlings were used in greenhouse studies as subjects representing fascicled and single needle conifers, respectively. Seedling canopy reflectance was measured on five treatment groups for each species under diffuse light in the greenhouse. Needle hemispherical reflectance and transmittance and percent vegetation cover (the percentage of the background covered by the canopy) were measured for each group. Each group of seedlings was then subjected to different levels of soil water potential through a cyclic watering schedule. After two and a half months of treatment at different levels, all measurements were repeated and the changes in parameters were calculated for each group. This repeated measures design made it possible to remove variations in the measured parameters, occurring among the groups at the initiation of the experiment, from the experimental design.

Changes in the reflectance of each treatment group were organized for analysis along a continuum of the average minimum soil water potential achieved during a group's watering cycle. Conclusions from a one-way analysis of variance of the changes associated with each group were strengthened because the treatments could be ranked and quantified, at least in terms of the minimum water potential obtained in a cycle. An interval ranking of treatments also permitted a graphical study of the trends associated with decreasing soil water potential. A maximum alpha level of 0.05 was accepted to indicate significance among the groups in an analysis of variance model. All possible pairwise comparisons were made between the changes in seedling canopy reflectance (post-experiment reflectance minus pre-experiment reflectance) for each of the groups of seedling canopies measured, using Scheffé-type simultaneous confidence intervals to test the null hypothesis that differences in the mean reflectance changes for a given pair of groups were equal to zero. An independent t-test was used to test the null hypothesis that the mean reflectance change calculated for each group was equal to zero.

Percent vegetation cover measurements were analyzed using the analysis of covariance model to adjust for pre-treatment variation. All possible pairwise comparisons were made between percent vegetation cover, adjusted for pre-treatment variation, using Scheffé-type confidence intervals. The experimental design was identical for both the pine and spruce seedling canopies and the following methods were applied in the same way to both species.

3. METHODS

Three year old nursery stock was transplanted, keeping the root and soil mass intact, to 20 cm diameter plastic pots in August 1975. The plants were allowed to acclimate to the greenhouse environment and were watered "as needed" by greenhouse gardeners until November 1975. The soil in the pots was main-

tained at field capacity (approximately minus 1 bar) during this period. A cyclic watering schedule was begun in late November 1975 and concluded in mid-February 1976. Five groups of eight plants each were placed on a bench in a random manner with the plants in each group arranged in two rows, four plants to a row. Pot edges were just touching, making a canopy arrangement 40 cm wide and 80 cm long (Figure 1).

The techniques used in this experiment can be divided into two major areas: the monitoring of soil water potential resulting from the planned watering schedule during the time interval between plant measurements; and the measurement of plant parameters (canopy reflectance, needle reflectance and transmittance, percent vegetation cover). Individual plant parameters were measured on the day in the watering cycle when soil water potential was lowest (i.e., the day just preceding a scheduled watering) to measure the maximum effect of soil water deficit in any one cycle.

Soil water potential was measured using a Wescor thermocouple psychrometer system (HR-33T Dew Point Microvoltmeter and PT-51 Thermocouple Psychrometers) after each psychrometer was calibrated using KCl solutions of known potential. The amount of water delivered to each group at any watering was held constant but the interval between waterings varied. Soil in the pots reached field capacity after watering and was allowed to dry to the specified potential before another watering. Actual intervals fluctuated between five and nine days based upon the average of soil water potential measurements ($n = \text{six per group}$). The watering cycle was the same for pine and spruce. Group 1 was maintained at field capacity and was not monitored. Group 5 seedlings received no water during the ten week experiment and since the soil in the pots containing these plants reached water potentials too low to be measured by the Wescor system, they were not monitored. Soil water potential was monitored in Groups 2 through 4. The precision of soil water potential measurements was probably no better than plus or minus fifteen percent, considering both sampling error and instrument reliability.

The reflectance of the seedling canopies was measured before the initiation of the watering cycles and at their conclusion. Canopy reflectance was measured during pre-dawn twilight hours or within seven hours after sunrise to avoid diurnal variation associated with a possible mid-day depression in plant water potential. Reflectance was measured at 450, 550, 600, 650, 700, and 780 nm. A Gamma Scientific spectroradiometer (Figure 1) was used together with a panel of known reflectance in a fashion identical to that discussed by Suits and Safir (1972). Canopy reflectance was measured at two view angles, vertical and at forty-five degrees, at randomly selected points over each group of seedlings. Six replications were made for each view angle. Early data showed a low variance for these six replications, and the sample size was reduced to four later in the experiment. In order to insure a constant background reflectance for all canopy reflectance measurements, the pots were covered with a square piece of posterboard (Figure 1).

The total hemispherical reflectance and transmittance of needles were measured with a Beckman DK-2 spectrophotometer. Needles were aligned in a single layer and gaps in the mosaic were compensated for by using a photographic technique. The six wavelengths measured by the Gamma radiometer were duplicated in the 400 to 800 nm wavelength interval on the Beckman instrument. Hemispherical spectral reflectance and transmittance were also measured at six points in the 1300 to 1950 nm band where reflectance and transmittance are sensitive to needle water content (Wiegand, et. al., 1972). Needle measurements were not replicated.

The density of the foliage in the canopy of each group of seedlings was indicated by measuring percent vegetation cover. Each group of seedlings was photographed and the percentage of the 40 by 80 cm background area covered by the canopy (percent vegetation cover) was computed by statistical dot tally on the negatives ($n = \text{eight}$).

4. RESULTS AND DISCUSSION

The reflectance of the pine and spruce canopies changed in a similar manner and only the pine data will be discussed at length. The plants in Groups 1, 2, and 3 seemed to be growing normally at the end of the experiment and were apparently not adversely affected by the soil water deficit experienced during the experiment. The reaction of the plants in Group 4 was mixed. All plants appeared to be dead in Group 5 as all of the foliage had turned yellow-brown by the end of the experiment. Changes in pine canopy reflectance measured from a vertical view (Figure 2) showed a general downward trend with decreases in potential at 780 nm and an upward trend at all other wavelengths. Reflectance changes in Group 5 were always significantly different from the other groups and the most significant separation between groups occurred at 650 and 780 nm. The analysis of variance was significant at every wavelength. Focusing on group reflectance changes from zero, the Group 1 canopy reflectance change was significantly greater than zero at 550, 700, and 780 nm. Groups 2 and 3 reflectance changes were not significantly different from zero except at 650 and 700 nm where a positive significant change occurred for Group 2. Reflectances in Groups 4 and 5 changed significantly from zero at all wavelengths. Pine seedling canopy reflectance observed from a forty-five degree view did not change as greatly as the vertical view data. A clear trend in the relationship between soil water deficit and reflectance change was only present at high levels of stress where positive changes in reflectance became larger, except at 780 nm where a clear trend was not evident at any level of stress.

The percent vegetation cover of pine canopies, as affected by the minimum water potential obtained in each group is shown in Figure 3. Pine seedlings did not flush during the experiment and since needles were fully extended during the previous growing season, all changes in percent cover were caused by needle orientation changes (drooping) except in group 1. Two plants died in Group 1 and reserve pine seedlings of differing size and geometric configuration replaced them. Needle droop began to become apparent in Groups 4 and 5 especially after the needles had turned yellow-brown. Defoliation was almost non-existent for the pine seedlings. Vegetation cover, as observed from a vertical view, showed a nonsignificant increase from its original level until a water potential of about minus twenty-five bars was reached and then decreased significantly. The forty-five degree view had a similar pattern with the increase continuing until about minus sixty bars and then decreasing. Differences between groups were not significant at the forty-five degree view angle.

Pine needle total hemispherical reflectance and transmittance were measured before and after the experiment. There appeared to be no differences between groups evident in the before-treatment data. The among group variation was no larger in the pre-experiment data than that shown in the post-experiment data for Groups 1-4 (Figures 4 and 5). The post-experiment data clearly showed reflectance changes from the pre-experiment reflectance values for only the lowest levels of potential (i.e., Group 5). Group 5 foliage appeared to be dead, yellow-brown in color, while the other foliage represented by the graphs appeared to be alive, green in color. Evidence is present to suggest an ordered increase in reflectance at 550 and 1700 nm for Groups 1 through 4 but this could not be tested statistically because the data were not replicated. Only live foliage is plotted for Group 4 although five of the eight plants in that group apparently died, their foliage turning yellow-brown. The dead foliage in Group 4 was assumed to have a reflectance pattern equal to that shown for Group 5.

There was a negative relationship between percent vegetation cover (Figure 3) and vertical view canopy reflectance (Figure 2) in the visible wavelength region where the background was more reflective than the needles (Figure 4) especially at 650 nm. Canopy reflectance was primarily a function of percent cover for Groups 1 through 3 as needle reflectance was unchanged at the minimum levels of soil water potential experienced in these groups (greater than minus twenty-five bars). Reduced cover and increased needle reflectance contributed

to the large increases in canopy reflectance evident in Groups 4 and 5. This trend was reversed at 780 nm as the background was less reflective than the needles (Figure 4) and needle reflectance decreased slightly at 780 nm as necrosis occurred in the plants experiencing high (minus sixty bars) levels of soil water deficit. The reflectance data for the forty-five degree view show that upward trends associated with increased soil water deficit were diminished relative to the vertical view data. Reductions in pine percent cover were mainly caused by needle droop which reduced horizontal foliage area (recorded from the vertical view) more than the combination of horizontal and vertical foliage area observed from the forty-five degree view.

The reflectance of the spruce seedling canopies changed in a manner similar to the pine canopies. Upward trends in canopy reflectance at a vertical view associated with an increasing soil water deficit were present at all wavelengths for spruce canopies. The downward trend at 780 nm noted for pine canopy reflectance was not present in the spruce data as infrared foliage reflectance was lower than background reflectance rather than higher as it was in the pine. As a result, decreases in foliage cover produced increases in canopy reflectance at all wavelengths. There was essentially no difference in the spruce reflectance changes recorded at a vertical view and those measured at a forty-five degree view angle. Reduction in spruce vegetation cover was caused by defoliation rather than drooping.

5. CONCLUSIONS

As inferred from seedling canopies under a diffuse light source, canopy density has a highly variable effect on canopy reflectance. When background reflectance is lower than foliage hemispherical reflectance, as it was for pine seedling canopies at 780 nm, canopy reflectance decreased with reduced vegetation cover. The opposite was true when background reflectance was higher than needle reflectance, as it was for pine seedlings at visible wavelengths and spruce seedlings at visible and infrared wavelengths. If conditions are similar to those experienced in the pine study, the 780 nm band provides an important reverse trend in reflectance, and should be included as a channel of remote sensor operation, possibly used in a ratio with a visible band that would maximize sensitivity to changes in vegetation cover. The infrared band does not provide unique information if the background is more reflective than the foliage in the infrared as well as in the visible bands.

Nothing could be found to support an argument for early or pre-visual detection of water stress in pine seedlings by measuring the changes in canopy reflectance and explaining canopy reflectance changes from observed variations in vegetation cover. Needle hemispherical reflectance or transmittance did not change at any wavelength until tissue necrosis (death, as inferred from yellow-brown foliage color) occurred and changes in the visible bands were almost as large as those occurring at any other wavelengths measured, including infrared water absorption bands (1425 and 1950 nm). Conclusions were identical for the spruce needles.

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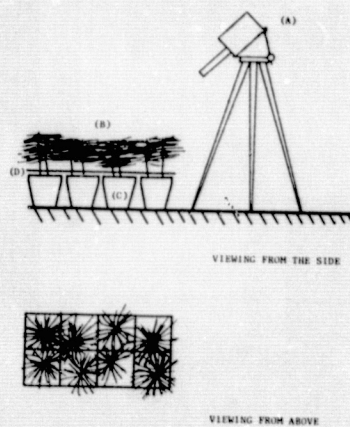


FIGURE 1. SEEDLING ARRANGEMENT. A diagram of the experimental set-up for measuring canopy spectral reflectance. The radiometer (A) is shown set for a 45° view measurement of seedling canopy (B) reflectance. The pots (C) are shown overlaid with the poster board background (D) used to provide constant background reflectance.

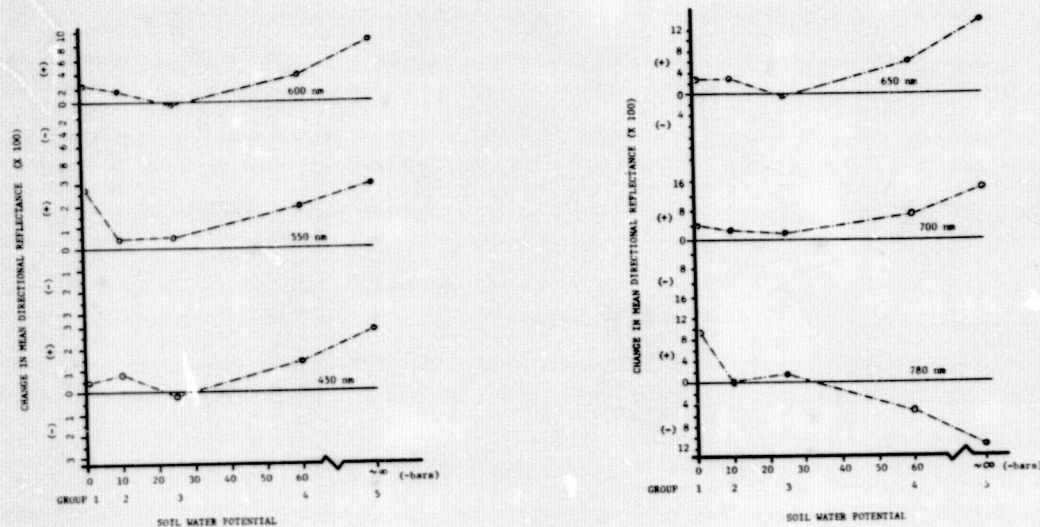


FIGURE 2. PINE CANOPY REFLECTANCE CHANGES. A graphical presentation of the trends in the mean reflectance changes measured for the pine seedling canopy at a vertical view angle. Reflectance changes are plotted over the minimum soil water potential obtained in each treatment group for six wavelengths.

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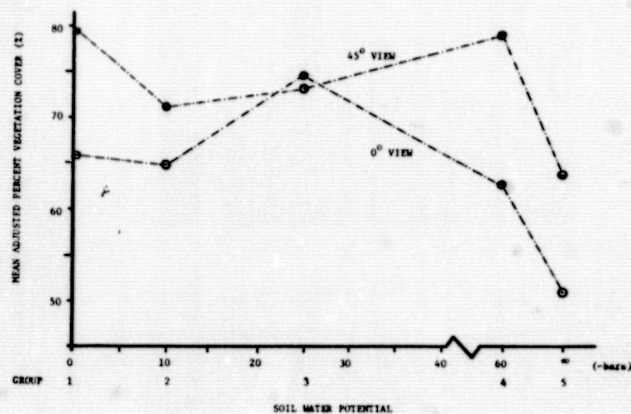


FIGURE 3. PERCENT VEGETATION COVER. A plot of adjusted mean percent vegetation cover for the pine canopy at a vertical and 45° view angle. Adjusted means are plotted upon the minimum level of soil water potential obtained for each treatment group during a watering cycle.

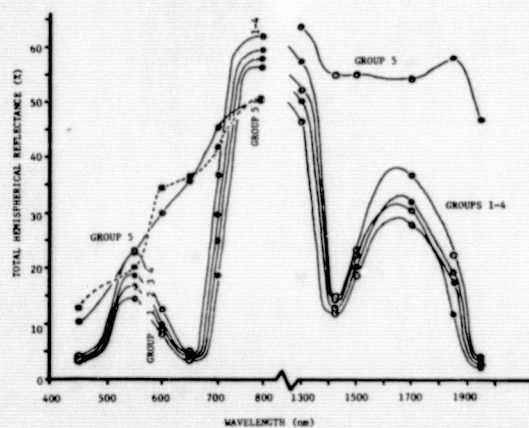


FIGURE 4. PINE NEEDLE REFLECTANCE. A plot of pine needle reflectance as measured after the conclusion of a ten week application of various levels of soil water stress to each group. Dotted line is the reflectance of the poster board background laid under the seedling canopies. Curves are hand fitted through the data points obtained from the adjusted graphical output of the Beckman radiometer. Group numbers are listed.

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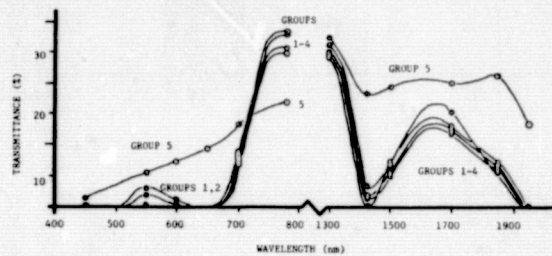


FIGURE 5. PINE NEEDLE TRANSMITTANCE. A plot of pine needle transmittance as measured after the conclusion of a ten week application of various levels of soil water stress to each group. Curves are hand fitted through the data points obtained from the adjusted graphical output of the Beckman radiometer. Group numbers are listed.

OMIT

DIGITAL ANALYSIS OF LANDSAT DATA FOR SURVEYING
NATURAL RESOURCES IN WESTERN SUDAN

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For a large fraction of the land area of the world no detailed survey or large scale map (greater than 1:100,000) of the soils, vegetation, surface hydrologic network, geology and land use has ever been done. This paper describes the cooperative research by Sudanese and Purdue University scientists to assess the utility and reliability of digital analysis of Landsat data for surveying the natural resources in the savanna of Sudan.

The savanna, between latitudes 11°N and 13°N, is a potentially productive area for livestock and crop production. A crucial need for any program of development, management and conservation of the natural resources of the area is a detailed survey of these resources.

The primary data source for this study was the digital data for Landsat scene numbers 1108-07482 and 1108-07484 obtained on 8 November 1972. Time of data acquisition occurred a few weeks after the rainy season. The Landsat data were free of clouds and were obtained when the atmosphere was relatively free of desert dust and the area exhibited a maximum of green vegetative cover.

The area of interest lies in the southeastern corner of Northern Kordofan Province and the northeastern part of Southern Kordofan Province. Important features in the study area are the Wadi (river) Abu Hahl which drains eastward toward the White Nile, tributaries of the Wadi, Jebel (hill) Ed Deir, extensive sand dunes, clay plains, a railway, many villages, and the large towns of Er Rahad and Umm Ruwaba.

Many of the problems encountered in the analysis and interpretation of multispectral data used in this study are the same as those encountered in many other areas of the world. Existing maps and surveys lack detail and accuracy; there is little or no aerial photographic data; logistics for obtaining essential ground observation data in the study area is generally complicated and expensive; and arrangements for aerial reconnaissance may be difficult if not impossible.

Visual interpretation of an image or photograph generally progresses from the observation of a few gross features to a recognition of more features and a delineation in greater detail. Digital analysis of multispectral data may easily begin with a separation of a scene into a large number of spectrally separable categories and then a process of generalization to combine different spectral classes. This process of moving from many classes to a lesser number of classes is particularly useful in the analysis of spectral data from a landscape where little or no ground observation data are available.

Visual examination of color composite images (scale 1:250,000) suggested that it would be reasonable to classify the study area into 20 to 25 spectral classes. Using a nonsupervised classification algorithm, analysts produced a computer printout map (scale 1:50,000) consisting of 25 spectrally separable classes. With limited ground observation data and a careful consideration of the spectral statistics of the 25 classes obtained from nonsupervised classification, a set of training samples for 13 new classes was selected. With this training set a supervised classification algorithm was used to produce a map of 13 new classes representing the following features:

1. Vertisols, dark swelling clays in the floodplain, non-vegetated
2. Vertisols, dark swelling clays in the floodplain, vegetated, natural
3. Alfisols, upland clay plain, medium density savanna woodland, acacia species dominant
4. Alfisols, upland clay plain, sparse vegetative cover, grasses predominant
5. Shallow sands on Alfisols, medium to sparse vegetative cover
6. Deep sands, cultivated standing crop, mostly millet
7. Deep sands, cultivated, harvested, little residue remaining from peanuts, sesame
8. Deep sands, uncultivated, medium density grass cover
9. Dense green vegetation, irrigated fields in Vertisols of floodplain
10. Dense green vegetation, trees along main channels of floodplain
11. Water of reservoir, deep, little or no aquatic vegetation
12. Water of reservoir, dense aquatic vegetation
13. Urban areas, villages.

A qualitative field evaluation of these classification results from 1972 data was made in November 1976. Obviously it was impossible to reconstruct the conditions and land use of the area as it was in 1972. However, the field evaluation, which included both ground inspection and aerial reconnaissance from an altitude of 1500 meters, indicated that recognition and delineation of important soils, vegetation, water, and land use features had been quite accurate. It was concluded that, had more and better ground observation data been available for training samples, more features could have been identified and mapped spectrally.

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USE OF CLEAR LAKES AS STANDARD REFLECTORS
FOR ATMOSPHERIC MEASUREMENTS

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ABSTRACT

A method is proposed for using clear lakes as dark backgrounds against which the atmospheric path radiance can be determined from satellite observations. If the path radiance can be determined to sufficient accuracy, the atmospheric extinction can be inferred with suitable radiative transfer models.

An extensive program of observation has been made to determine the magnitude and variability of the various contributors to the total radiance observed by a satellite.

It is shown that the volume and surface reflectance contributions (in the absence of sunglint) are small, constant, and can be modelled accurately enough to make these an insignificant source of error. The sunglint radiance observed in this investigation may be a significant source of error.

Comparison of observed path radiances with those calculated by the Turner-Spencer (1972) model show systematic differences which could be explained either by systematic errors in the calibration of the observations or by shortcomings of the model.

It is shown that atmospheric extinction can be inferred from the path radiance observation after systematic differences between the model and observations are removed.

The individual sources of error in the path radiance and extinction coefficient estimates are determined, and the total error in these estimates is calculated, with and without sunglint. It is shown that the technique proposed here could be an accurate and reliable means of estimating path radiance and atmospheric extinction from satellite observations over clear lakes.

1. INTRODUCTION

One of the fundamental requirements of remote sensing is the ability to measure intrinsic properties of the target of interest with a minimum of confusion. In the case of multispectral remote sensing, one wishes to infer the spectral reflectivity of targets in the scene from their spectral radiances as measured by the remote sensor. The presence of the earth's

atmosphere significantly complicates this task, especially with satellite observations.

A list of symbols and definitions used in this paper is given in Table I.

The radiance observed by a satellite in a given spectral band can be written as:

$$L_{\text{sat}} = H_{\text{sun}}^0 \exp(-\tau/\cos Z_{\text{sun}}) \cos Z_{\text{sun}} r_c \exp(-\tau/\cos Z_{\text{sat}}) + H_{\text{sky}} r_d \exp(-\tau/\cos Z_{\text{sat}}) + L_p \quad (1)$$

where r is the bidirectional reflectivity for collimated irradiance and r_c is the c reflectivity of diffuse irradiance. If one assumes that $r_c = r_d = r$, one can solve for r :

$$r = \frac{(L_{\text{sat}} - L_p) \exp(\tau/\cos Z_{\text{sat}})}{H_{\text{tot}}} \quad (2)$$

where we have written

$$H_{\text{tot}} = H_{\text{sun}}^0 \exp(-\tau/\cos Z_{\text{sun}}) \cos Z_{\text{sun}} + H_{\text{sky}} \quad (3)$$

Hence to obtain an estimate of the reflectance of a target we must first subtract the path radiance, L_p , which is the radiance scattered into the line of sight by the atmosphere. Then we can multiply by the correction factor, $\exp(\tau/\cos Z_{\text{sat}})/H_{\text{tot}}$. H_{tot} , the total downwelling irradiance on a horizontal surface, depends weakly on the extinction coefficient τ and can be estimated from radiative transfer theory once τ is known. Thus, there are two important variables, L_p and τ , which are necessary to convert observed radiances into intrinsic reflectances. Furthermore, L_p and τ can be related through radiative transfer theory, although accurate results then require additional information such as the phase function of atmospheric scatterers (Turner, Malila, and Nalepka, 1971).

2. PROPOSED METHOD

The method proposed here is to use the numerous oligotrophic (low-nutrient level) lakes in the Canadian Shield as standard dark backgrounds against which the atmospheric path radiance can be measured. Then the extinction coefficient could be estimated through suitable models. Although this method would not be applicable for scenes lacking oligotrophic lakes, it is hoped that a better understanding of the variability of some atmospheric parameters would result from the application of this technique.

The radiance observed over a water body at satellite altitudes is the sum of a number of terms:

$$L_{\text{sat}} = (H_{\text{tot}} r_{\text{vol}} + H_{\text{sky}} r_{\text{surf}} + H_{\text{sun}} r_g) \exp(-\tau/\cos Z_{\text{sat}}) + L_p \quad (4)$$

or

$$L_{\text{sat}} = (L_{\text{vol}} + L_{\text{surf}} + L_g) T + L_p \quad (5)$$

Figure 1 is a schematic representation of the various terms in equation (4), while Figure 2 shows the relative magnitude of the four terms contributing to the total radiance in the four LANDSAT bands for a typical day (May 27, 1976).

To estimate the path radiance from the satellite, it is necessary to subtract $(L_{\text{vol}} + L_{\text{surf}} + L_g) T = L_{\text{lake}} T$; that is, the radiance of the lake times the atmospheric transmission. As shown in Figure 2, this is a small correction, so relatively large errors can be tolerated. Under high winds and high solar elevation, however, the radiance due to sunglint, L_g , can become

a significant source of error. This is discussed further in Section 5.7.

Radiative transfer theory allows one to calculate the path radiance expected at satellite altitudes if the extinction coefficient, τ , is known for each wavelength. (Turner, Malila, and Nalepka, 1971; Turner and Spencer, 1972). Therefore, if one calculates L_p for a number of different τ 's for the geometry appropriate for a particular observation, the observed L_p can be used to infer τ from the table.

The Environmental Research Institute of Michigan (ERIM) radiative transfer model of Turner and Spencer (1972) was chosen for this investigation because it was well documented in the literature, gave good results for other investigators, and was relatively easy to implement.

3. THE OBSERVATIONS

In order to verify the method of atmospheric parameter estimation proposed in Section 2, a comprehensive program of ground, airborne, and satellite observations was undertaken to test the assumptions and models. The observational program included:

- A. Airborne observations of the total upwelling radiance in the four LANDSAT bands over nine lakes in the Canadian Shield north of Ottawa to verify their spatial and temporal homogeneity as dark background targets.
- B. Colour and black and white aerial photography to record the sunglint pattern and any anomalous colours which could indicate eutrophic water.
- C. Ground observations on and near one lake (McGregor Lake) of H_{tot} , H_{sun} , H_{sky} , L_{sky} , $L_{surf} + L_{vol}$, and L_{vol} in the four LANDSAT bands. Sky observations were made in Ottawa on days of LANDSAT 1 overpasses when the sky was partly cloudy.
- D. Wind speed and direction for sunglint calculations.
- E. Wide angle (170°) colour photography of the sky to record the sky condition at the times of H_{sky} observations and aircraft and LANDSAT overpasses.
- F. Water colour measurements with a submersible photometer to verify the temporal invariance of McGregor Lake underwater reflectances.
- G. LANDSAT observations in the form of false colour prints and computer compatible tapes.

Table II is a log of dates and observations.

The airborne radiance measurements were made with the CCRS Miller-Pieau Photometer (MPPH), a four channel nadir viewing radiometer which also measures the total downwelling irradiance by means of a diffuser on the roof of the DC-3 aircraft. (Miller and Pieau, 1975).

The airborne photography was taken with two Vinten 70 mm cameras with 3 inch focal length lenses, loaded with Kodak 2445 colour negative and 2405 black and white film. McGregor Lake was also photographed with a Wild-Heerbrugg RC-10 9 inch x 9 inch camera with an 88 mm focal length lens and Kodak 2405 film. On September 12th, the Vinten cameras were not available and the RC-10 had a 6 inch focal length lens and Kodak 2445 film.

The ground radiance and irradiance observations were made with a Bendix RPMI radiometer. Photography was obtained with a Nikkormat EL 35 mm camera with a Fisheye-Nikkor 16 mm focal length lens. Wind speed and direction, and air temperature were recorded with a Meteorology Research International Mechanical Weather Station.

4. CALIBRATION OF THE SENSORS

4.1 BENDIX RPMI

The Bendix RPMI is a radiometer with a white diffusing screen, a filter wheel containing four LANDSAT band filters and a silicon photodiode in series (Rogers and Peacock, 1973). The photodiode signal is amplified and displayed on an analog meter. For irradiance observations the diffuser views a hemisphere, while for radiance observations a collimating tube can be attached which restricts the field of view. The angular sensitivity of the RPMI with and without the collimating tube was measured by the National Research Council of Canada (Budde, 1976). Since there are no imaging optics, the radiance response is not uniform across the field of view, but rather quasi-Gaussian, with a full width at half maximum of 8° , and very extended wings. These wings result from reflection from the inner wall of the tube, which is black anodized aluminum with no light baffle.

The radiance response of the white diffuser deviates significantly from an ideal cosine response at large angles, as shown in Figure 3. This can introduce significant error into irradiance readings. This error can be corrected if the irradiance is collimated and coming from a known angle as in the case of sunlight, or if it comes from a uniform hemisphere. For the case of a uniform hemisphere, the RPMI signal would be .80 of its expected value, because of the diffuser deviation from cosine response.

The RPMI was calibrated for irradiance and for radiance separately. The irradiance calibration was performed as suggested by Rogers and Peacock (1973). The solar irradiance, H_{sun} , was observed at a wide range of zenith angles on eight occasions. The eight estimates of solar irradiance at zero air mass, H_{sun}^0 , were averaged. The absolute value of H_{sun}^0 in the four LANDSAT bands was calculated from Thekaekara's (1974) data on the extraterrestrial solar spectral irradiance. The ratio of the absolute to the observed value of H_{sun}^0 was taken as the calibration factor for each band. These are listed in Table III.

The radiance calibration factors for the RPMI were measured with a Gamma Scientific Model 220-ID radiance source, serial number AG126. The radiance calibration constants are given in Table III.

4.2 MILLER-PIEAU PHOTOMETER

The radiance and irradiance calibration of the MPPH was performed using the RPMI as a reference sensor. On June 4, 1976, a cloud-free day, the RPMI and MPPH were mounted above a diffuse white reflectance panel exposed to direct sunlight. The relative meter readings were recorded, allowing a radiance calibration of the MPPH via the RPMI radiance calibration.

Similarly for irradiance calibration, the diffusers of the MPPH and RPMI were mounted horizontally and exposed to direct sunlight. This allowed an irradiance calibration of the MPPH via the RPMI irradiance calibration. The MPPH radiance and irradiance calibration factors are given in Table III.

4.3 LANDSAT

LANDSAT compressed digital values were converted to a linear scale with all sensors in each band equalized to a reference sensor using the procedure described by Strome, Vishnubhatla, and Guertin (1975). The corrected digital values were then converted to radiances using the Goddard Space Flight Center procedure (Thomas, 1975). However, the Canadian LANDSAT image processing system is not able to obtain all of the available calibration data. Instead, data from only eight calibration wedges per scene were available to calculate the gain and offset of the reference sensor for each band. The resulting uncertainty in gain and offset estimates are shown in Table III. All values are on a 256 level (8 bit) scale.

5. ANALYSIS OF THE OBSERVATIONS

5.1 ATMOSPHERIC EXTINCTION

The solar irradiance, H_{sun} , was measured frequently on each day of observations. The extinction coefficient, τ , in each LANDSAT band can be calculated from each observation of H_{sun} from the equation:

$$\tau = \frac{\ln(H_{\text{sun}}^0) - \ln(H_{\text{sun}})}{\sec Z_{\text{sun}}} \quad (6)$$

For six relatively cloud-free dates, the extinction coefficient at the time of LANDSAT overflight was calculated as an average of several independent estimates of τ near the time of LANDSAT overflight. These are listed in Table IV.

The mean τ for the six days and the standard deviation of the average are given at the bottom of Table IV. These mean τ 's agree well with values for a standard atmosphere given by Valley (1965).

5.2 MEAN BACKGROUND ALBEDO

The Turner-Spencer (1972) model requires an estimate of the mean background albedo of the area over which the path radiance is to be calculated. For our work we estimated these from digital LANDSAT data using the formula:

$$\bar{\rho} = \pi \bar{L}_{\text{sat}} / (H_{\text{sun}}^0 \cos Z_{\text{sun}}) \quad (7)$$

where $\bar{L}_{\text{sat}}$ is the average radiance of a 512×512 LANDSAT pixel area centered near McGregor Lake. There were no significant changes on $\bar{\rho}$ throughout the period from May 27, 1976 to September 30, 1976, so the average values given in Table V were used for all model atmosphere calculations in this experiment. The errors quoted are the standard deviation of a single estimate of $\bar{\rho}$.

5.3 TOTAL AND DIFFUSE DOWNWELLING IRRADIANCE

The total irradiance, H_{tot} , and the diffuse irradiance, H_{sky} , were measured frequently as part of the ground observations. H_{tot} was measured with the RPMI diffuser adjusted to the local horizontal. H_{sky} was measured by shading the RPMI diffuser with a 5 cm occulting disk held approximately 1 m away, subtending .05 radians or approximately $2\frac{1}{2}^\circ$. Figure 3 shows the ratio of the observed H_{tot} to that predicted by the Turner radiative transfer model, using the extinction coefficients given in Table IV.

Figure 3 also shows the ratio of the actual diffuser response to the desired cosine response. We see that the ratio of observed to calculated total irradiances follows the same form as the ratio of actual to ideal response, but lies slightly below. This is what we would expect, since the greatest contribution to H_{tot} is $H_{\text{sun}} \cos Z_{\text{sun}}$. The remaining discrepancy is due to diffuse (sky) irradiance which is calculated by the Turner model but not measured because of the deviation of the diffuser from ideal cosine response.

The ratio of the measured to the predicted sky irradiance was also determined for all of the sky irradiance observations. This ratio does not vary significantly with solar zenith angle, nor with wavelength. The average of this ratio for all observations were $.46 \pm .08$. So only 46 per cent of the irradiance expected from the Turner model is actually observed. There are at least two factors contributing to this shortfall. The first is the deviation of the diffuser response from the ideal cosine function. As discussed in Section 4, this would result in a measurement of only 80 per cent of the actual value of sky irradiance, H_{sky} , for a uniformly illuminated hemisphere. The second factor is the solar aureole. Much of the energy which goes into H_{sky} is light scattered

through very small angles. This appears as a bright halo, or aureole around the sun. Since our occulting disk subtended 2.5° , at the diffuser, and the sun only subtends 0.5° , much of the aureole light near the solar limb will be blocked by the occulting disk. But in the sense that the sky irradiance, H_{sky} , should represent the quasi-uniform diffuse sky irradiance, the aureole light should be omitted, since it comes from a small area in the vicinity of the sun.

5.4 LAKE RADIANCES

Airborne photographic and radiometric data were obtained on three nearly clear days over nine lakes spread over a 20 km (E-W) by 30 km (N-S) area centered approximately 30 km north of Ottawa. Photographic data were obtained on a fourth date.

Table VI lists the mean value and standard deviation of r_{lake} , the lake reflectance for ten flight lines over the nine lakes, where $r_{lake} = L_{lake}/H_{tot}$. The variations in r_{lake} among the three days are due to changing sky conditions. Most of the lake radiance is surface reflected sky radiance, which is quite sensitive to atmospheric extinction, while the total irradiance, H_{tot} , is not. Therefore, we see significant increases in L_{lake} on hazy days like June 14, but H_{tot} remains nearly invariant.

It appears that the lakes form a homogeneous class of dark reflectors as was originally intended. These lakes were chosen from many having very low band 7 signals on 1975 LANDSAT images. Thus it appears that relatively simple procedures can be used to find lakes suitable for the proposed atmospheric correction procedure.

Table VII shows the average radiance of McGregor Lake from airborne observations taken within 10 minutes of the time of the LANDSAT overpass. Measurements from a boat for five dates are also shown. A linear regression of the twelve values common to both surface and airborne data gives:

$$L_{aircraft} = (0.92 \pm 0.1) L_{boat} - (0.007 \pm 0.0003) \quad (8)$$

with a correlation coefficient of 0.89. Values of $L_{aircraft}$ have been calculated for August 25 and September 30 from L_{boat} and are also shown in Table IV. It is encouraging that one or two measurements made at one location can give results which are typical of the entire lake, since this means that expensive aircraft coverage is not always necessary in an experiment such as this.

5.5 WATER VOLUME REFLECTANCE

The observations with the radiometer collimating tube immersed in the water are measurements of the volume radiance of the water since the tube prevents the water surface from being illuminated from above. Table VIII gives the volume reflectance measured on six relatively clear days. We define $r_{vol} = L_{in}/H_{tot}$ where L_{in} is the observed radiance with the collimator tube immersed in the water, and H_{tot} has been calculated from the Turner-Spencer model with extinction coefficients for the date of observation.

McCluney (1974), Jain and Miller (1977), and Gordon and Brown (1973) have computed the irradiance reflectance of the flat ocean in terms of the scattering albedo (ω_o) of water for three representative phase functions. Phase functions A and B may be used as approximate functions for LANDSAT bands 5 and 4 respectively. Comparing the above calculations with observations of volume reflectance, we infer that the scattering albedo is not likely to be higher than 0.3 for band 4, and 0.4 for band 5. The volume reflectance varied very little during the measurements from May to September. In the region $0 < \omega_o < 0.4$ this result is expected because reflectance is a weak function of scattering albedo. A low value of ω_o in the red region of the spectrum is a result of a low scattering coefficient (or of low particulate concentration). Since the change in the volume reflectance of water is a very weak function of the water parameters in

these lakes, and since the volume reflectance contributes very little to the total radiance of the lake, the average reflectances given in Table VIII can be considered typical of oligotrophic lakes.

5.6 WATER SURFACE REFLECTIVITY

The surface reflectivity of water for vertically incident light varies from .0204 at 589 nm to .0191 at 1256 nm. (Calculated from indices of refraction given by Jenkins and White, 1957). Cox and Munk (1956) shows that the reflectivity of a water surface is essentially independent of sea state, for vertical viewing, as long as whitecaps do not form. Therefore, we adopt $r_{\text{surf}} = 0.02$ for all calculations in this study.

5.7 SUNGLINT REFLECTIVITY

Cox and Munk (1954) used photographs of the sunglint pattern to study wave slope statistics, and derived an empirical model to fit their observations. We have used the Cox-Munk model to calculate the effective sunglint reflectivity as a function of wind speed for a range of solar altitudes. These curves are shown in Figure 4.

Table IX gives the radiance one would expect from sunglint according to the Cox-Munk model for the three dates where aircraft radiances are available. Sunglint radiances of this size should be apparent as a difference between the airborne radiances, where the radiometer views many waves at a time, including some causing sunglint, and the boat-based radiances, which do not include sunglint. The data in Table VII show that the airborne radiances are not significantly greater than the boat radiances. This indicates that the Cox-Munk model, which has been established over the open ocean, predicts too much sunglint for lakes of a few kilometers in size.

The aerial photographs taken simultaneously with the airborne radiometer observations generally show a small number of glinting waves within the radiometer field of view. Occasionally, however, the sunglint patch is distorted, presumably by surface wind gusts, and a large amount of sunglint is suggested. At these times the radiometer does show a significant increase. The sunglint radiance sometimes exceeds the values shown in Table IX on these occasions.

Table X shows the average monthly wind speed, in m/sec, for the last three years, and a forty year average, taken from Ottawa Airport records. A correlation of wind speeds measured on McGregor Lake against those at the Ottawa Airport shows a slope of $0.76 \pm .15$, with a correlation coefficient of 0.83. The lower speeds recorded on the lake presumably are due to shielding of the lake by the surrounding terrain.

The winds recorded during this experiment are typical of summer months in Ottawa. Under these conditions, sunglint radiance is not a significant fraction of the total radiance of a lake.

From Figure 4, it is apparent, however, that sunglint can become quite important under conditions of high wind, particularly for high solar elevation angles. Therefore, more work is needed to determine the relative occurrence of high winds on clear days in the late spring and early summer at low Canadian latitudes, and to determine whether the Cox-Munk model is valid for lakes larger than studied here.

6. ATMOSPHERIC PATH RADIANCE

Of the dates given in Table II, we have six for which relatively clear LANDSAT observations are available. For each of these six dates, a computer compatible tape of the LANDSAT data was processed on the CCRS image Analysis System (Goodenough 1977). For each of the nine study lakes, the mean digital level was determined in each LANDSAT band, and converted to radiance as discussed in Section 4.3. The mean radiances over the nine lakes and standard deviations of a single lake radiance are given in Table XI. This again demonstrates that these oligotrophic lakes form a homogeneous class. On hazier days such as June 14, the standard deviation of a single lake observation is larger, presumably because of a less homogenous atmosphere.

Equation (5) can be solved for the path radiance L_p in terms of L_{sat} , L_{lake} and T . We can calculate the atmospheric transmission T from the value of the extinction coefficient, τ , given in Table IV, and use values of L_{lake} given in Table VII. For the latter we have aircraft observations for May 27, June 14 and September 12. For August 25 and September 30, we have boat observations which can be converted to equivalent aircraft observations by means of equation (8). For June 5 we can use $r_{surf} = .02$, r_{vol} from Table VIII, and assume r_g is negligible as indicated from our observations of May 27 and June 14, and from the fact that on June 5, the wind speed was less than 1.5 m/sec. The total irradiance H_{tot} , and sky irradiance, H_{sky} , can be calculated from the observed value of τ given in Table IV, and multiplied by the above values of r_{vol} and r_{surf} , to give the expected values of L_{lake} given in Table VII.

Table XII gives the values of L_p calculated from the data in Tables IV, VII and XI. Table XII also lists values of L_p calculated with the Turner-Spencer (1972) model with the observed values of τ (in Table IV) and the values of the mean background albedo given in Table V as input. (Deirmendjian's (1969) Haze L aerosol phase functions, interpolated for the LANDSAT bands, were used for these calculations).

Figure 5 shows the model values of L_p plotted against the observed values. A straight line has been fitted to the values for each band and to averages of bands 4-6 and bands 4-7 by linear regression. The regression coefficients are given in Table XIII.

No band 7 radiance is available for June 5, since this was a LANDSAT 1 pass, and band 7 is not calibrated on LANDSAT 1. The September 12 data show the effects of cirrus clouds, which were observed and photographed over McGregor Lake at the time of LANDSAT overpass. The data from this date have not been used in calculating the regressions shown in Table XIII.

The fact that the best fit lines do not have unity slope and zero intercept indicates a systematic difference between theory and observation. The data presented here are inadequate to determine whether this discrepancy is caused by systematic errors in the observations, such as the absolute calibration of the LANDSAT sensors, or by some shortcoming in the Turner-Spencer model.

7. EXTINCTION COEFFICIENTS CALCULATED FROM PATH RADIANCE

As discussed in Section 2, we would like to be able to estimate the extinction coefficient, τ , in each band from the path radiances, L_p , estimated over oligotrophic lakes.

In the Turner-Spencer (1972) model, L_p is a very complicated function of atmospheric extinction, τ , and the illumination and viewing geometry. Rather than attempt an algebraic solution for τ in terms of L_p , we used the model to calculate L_p as a function of τ for the geometry applicable on each of the six dates listed in Table XII. These calculated curves were then used graphically to solve for τ in terms of the observed L_p in each band for each date.

The calculated values of τ are given in Table IX, and plotted as a function of the observed values in Figure 6. Table XIII gives the slopes, intercepts, and correlation coefficients of a straight line for each band and for averages of bands 4-6 and bands 4-7. The calculated extinction coefficients are systematically higher than the observed coefficients, which is a reflection of the fact that the Turner model gives systematically low path radiances (Section 6). The relatively small amount of scatter in the data and high correlation coefficients indicate that a straight line is adequate to describe the relationship between the observed and calculated extinction coefficients.

The scatter in both the path radiance and the extinction coefficient data decreases significantly when three and four band averages are used. This

indicates that there is a high degree of correlation among the four bands in both the path radiances and the extinction coefficients, and that our errors are primarily random rather than systematic. Therefore, we should expect to achieve good estimates of atmospheric extinction from satellite-measured path radiances over oligotrophic lakes if we can measure the path radiance to sufficient accuracy, as discussed in Section 8.

8. ERROR ANALYSIS

8.1 PATH RADIANCE

We can write an equation for the root mean square (rms) error in a single estimate of path radiance in terms of the rms error in each of the terms of equation 4:

$$E_{L_p} = \left[\left(\frac{\partial L_p}{\partial L_{sat}} \delta L_{sat} \right)^2 + \left(\frac{\partial L_p}{\partial H_{tot}} \delta H_{tot} \right)^2 + \left(\frac{\partial L_p}{\partial r_{vol}} \delta r_{vol} \right)^2 + \left(\frac{\partial L_p}{\partial H_{sky}} \delta H_{sky} \right)^2 + \left(\frac{\partial L_p}{\partial r_{surf}} \delta r_{surf} \right)^2 + \left(\frac{\partial L_p}{\partial H_{sun}} \delta H_{sun} \right)^2 + \left(\frac{\partial L_p}{\partial r_g} \delta r_g \right)^2 + \left(\frac{\partial L_p}{\partial \tau} \delta \tau \right)^2 \right]^{\frac{1}{2}} \quad (9)$$

Taking $\cos Z_{sat} = 1$, we find the following partial derivatives:

$$\frac{\partial L_p}{\partial L_{sat}} = 1$$

$$\frac{\partial L_p}{\partial H_{tot}} = r_{vol} e^{-\tau};$$

$$\frac{\partial L_p}{\partial r_{vol}} = H_{tot} e^{-\tau}$$

$$\frac{\partial L_p}{\partial H_{sky}} = r_{surf} e^{-\tau};$$

$$\frac{\partial L_p}{\partial r_{surf}} = H_{sky} e^{-\tau}$$

$$\frac{\partial L_p}{\partial H_{sun}} = r_g e^{-\tau};$$

$$\frac{\partial L_p}{\partial r_g} = H_{sun} e^{-\tau}$$

$$\frac{\partial L_p}{\partial \tau} = L_{lake} e^{-\tau};$$

Therefore, equation (9) can be re-written:

$$E_{L_p} = \left\{ \delta L_{sat}^2 + \left[(r_{vol} \delta H_{tot})^2 + (H_{tot} \delta r_{vol})^2 + \left(\frac{r_{surf} \delta H_{sky}}{\pi} \right)^2 + \left(\frac{H_{sky} \delta r_{surf}}{\pi} \right)^2 + (r_g \delta H_{sun})^2 + (H_{sun} \delta r_g)^2 + (L_{lake} \delta \tau)^2 \right] \exp(-2\tau) \right\}^{\frac{1}{2}} \quad (10)$$

In this error analysis we neglect systematic errors on the grounds that they should be invariant with time and, therefore, will affect all data to which this method is applied similarly. As more comparisons between theory and observation become available, it should be possible to reduce the magnitude of any systematic errors.

Table XIV gives typical values for each term of equation 10 for the extinction coefficient of a standard atmosphere given in Table IV and a solar elevation of 60° . The values of $\delta\tau$ for band 4 have been calculated using statistics for τ in rural areas tabulated by Potter (1974). Values of $\delta\tau$ for the other bands have been calculated proportionally:

$$\frac{\delta\tau}{\tau} = \frac{\delta\tau_4}{\tau_4} \quad (11)$$

using the values of τ for a standard atmosphere. Values of δH_{tot} , δH_{sun} and δH_{sky} have been calculated numerically using the Turner-Spencer (1972) model and values of $\delta\tau$ given above. The value of δr_g shown in Table X has been calculated for the Cox-Munk (1954) model with a wind speed of 3 m/sec and standard deviation of 2 m/sec, and with a 45 degree angle between the wind direction and the solar azimuth.

Final values for δL_p have been calculated with δr_g both included and omitted. The latter case applies to conditions of lower solar elevation, such as more northerly latitudes, or lower solar declination such as in August and September. Since the sunglint radiance we observed was considerably less than that predicted by the Cox-Munk model, the lower values of δL_p obtained by omitting δr_g may be more realistic.

Even when the sunglint uncertainty is included, we should be able to measure path radiance to a relative accuracy of 10 to 20 per cent on typical days and considerably better on hazy days. When sunglint is not a problem we should be able to reduce the uncertainty by approximately a factor of 2. In terms of digital values on the LANDSAT 2 radiance scale, we should be able to correct LANDSAT data for path radiance to one part in 64 if sunglint is a significant source of uncertainty and to one part in 128 under conditions where sunglint is negligible.

8.2 EXTINCTION COEFFICIENT

If we know the expected error in path radiance, we can calculate $\delta\tau$, the uncertainty in our estimate of atmospheric extinction, from

$$\delta\tau = \frac{\partial\tau}{\partial\tau_T} \frac{\partial\tau_T}{\partial L_p} \delta L_p \quad (12)$$

where τ_T is the Turner-Spencer (1972) model extinction coefficient, $\partial\tau_T/\partial L_p$ can be calculated numerically from the model, and $\partial\tau/\partial\tau_T$ is the empirical relationship between the observed and the model extinction coefficients, as shown in Figure 6 and Table XIII

Table XIV gives values for $\partial\tau_T/\partial L_p$, $\partial\tau/\partial\tau_T$, and for $\delta\tau$, both including and neglecting sunglint uncertainties in L_p . Since the slope of τ as a function of L_p is quite steep, especially for band 5, relatively small errors in estimating L_p can cause large errors in the estimate of τ .

If we compare lines 30 and 31 of Table XIV with line 15, (the rms uncertainty in τ if we have no a-priori knowledge of the atmosphere), we see that the proposed technique reduces the rms error in τ considerably.

9. CONCLUSIONS

- A. Oligotrophic lakes provide suitable dark backgrounds against which atmospheric path radiance can be measured. Their volume and surface reflectances (in the absence of sunglint) are small and constant and can be accurately modelled.
- B. Sunglint is not a significant source of radiance at solar elevations of 55° and less and winds of up to approximately 3.5 m/sec over lakes of a few kilometers in size. More work is necessary to determine the importance of sunglint over larger lakes and at higher wind speeds.

- C. The technique investigated here could be used, without further refinement, to estimate path radiance to an accuracy of approximately $\pm .025 \text{ mw/cm}^2 \text{ str}$ in LANDSAT bands 4-6 and $\pm .05 \text{ mw/cm}^2 \text{ str}$ in LANDSAT band 7. This corresponds to approximately one level out of 64 in each band.
- D. It is possible to infer the atmospheric extinction coefficient from the measured path radiance, if an empirical correction is applied to the Turner-Spencer (1972) model. The accuracy expected in the extinction coefficient estimates is approximately $\pm .05$ in LANDSAT band 4, $\pm .08$ in band 5, $\pm .03$ in band 6 and $\pm .04$ in band 7.

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TABLE I. LIST OF SYMBOLS

H_{sun}^0	- Solar irradiance at the top of the earth's atmosphere
H_{sun}	- Solar irradiance at the earth's surface on a plane perpendicular to the line of sight to the sun.
H_{sky}	- Irradiance on a horizontal surface from the sky, not including the direct solar contribution.
H_{tot}	- Total (solar plus sky) irradiance on a horizontal surface.
L_{sat}	- Radiance observed by an earth satellite in a particular spectral band.
L_p	- Path radiance observed above the earth's atmosphere.
L_{vol}	- Radiance observed above a body of water due to light scattered below the surface of the water.
L_{surf}	- Radiance observed above a body of water due to sky (diffuse) radiance reflected by the surface of the body of water.
L_g	- Radiance observed above a body of water due to specularly reflected sunlight.
L_{sky}	- Radiance observed from the sky in a particular direction.
L_{lake}	- Total radiance observed above a body of water = $L_{\text{vol}} + L_{\text{surf}} + L_g$, but not including L_p .
r	- Reflectance. We use an observational quantity here, namely the ratio of observed upwelling radiance to the downwelling irradiance. This differs from the more frequently used ρ or R which is the ratio of upwelling to downwelling irradiance. For Lambertian reflectors ρ (or R) = πr . Often this factor of π is implicitly assumed and used in the literature even in cases, such as reflection by a water surface, when the Lambertian assumption is obviously not valid. We adopted the above definition of r to avoid this problem. Subscripts for r are the same as for L .
T	- Atmospheric transmission = $e^{-\tau}$
Z_{sun}	- Solar zenith distance
Z_{sat}	- Satellite zenith distance
τ	- Atmospheric extinction coefficient
4	- LANDSAT spectral band 4 500-600 nm width 100 nm
5	- LANDSAT spectral band 5 600-700 nm width 100 nm
6	- LANDSAT spectral band 6 700-800 nm width 100 nm
7	- LANDSAT spectral band 7 800-1100 nm width 300 nm
ρ	- Albedo, or ratio of upwelling irradiance (integrated over 2π steradians), to downwelling irradiance (integrated over 2π steradians). For a Lambertian reflector $\rho = \pi r$.

TABLE II. OBSERVATION DATES AND PLATFORMS

DATE	SKY CONDITION	LOCATION OF GROUND OBSERVATIONS	AIRCRAFT	LANDSAT (1 or 2)
9 May 76	Overcast	McGregor Lake	No	2
27 May	Clear	McGregor Lake	Yes	2
5 June	Clear	Ottawa	No	1
14 June	Very Hazy	McGregor Lake	Yes	2
23 June	Heavy Cumulus	McGregor Lake	No	1
20 July	Heavy Cirro-stratus	McGregor Lake	No	2
7 August	Heavy Cirro-stratus (broken)	McGregor Lake	No	2
25 August	Thin Cirrus (broken)	McGregor Lake	Yes*	2
12 September	Thin Cirrus	McGregor Lake	Yes	2
21 September	Broken Cumulus	Ottawa	No	1
28 September	Clear	Ottawa	No	None
30 September	Clear	McGregor Lake	No	2
18 October	Thick Cumulus	McGregor Lake	Yes	2

* Photography Only

TABLE III. INSTRUMENTAL CALIBRATION FACTORS

	<u>BAND</u>			
<u>QUANTITY</u>	4	5	6	7
RPMI irradiance calibration factor (for mw/cm^2)	$.1204 \pm .0025$	$.0875 \pm .0015$	$.09515 \pm .0015$	$.2633 \pm .0036$
RPMI radiance calibration factor (for $\text{mw}/\text{cm}^2\text{str}$)	9.224	7.528	8.179	24.64
MPPH irradiance calibration factor (for mw/cm^2)	3.529×10^{-3}	2.049×10^{-3}	6.836×10^{-2}	3.966×10^{-3}
MPPH radiance calibration factor (for $\text{ms}/\text{cm}^2\text{str}$)	1.359×10^{-4}	1.060×10^{-4}	3.231×10^{-3}	1.093×10^{-4}
Uncertainty in LANDSAT gain (on an 8-bit scale)	3.80	2.45	3.56	2.65
Uncertainty in LANDSAT offset (on an 8-bit scale)	0.92	0.34	0.42	1.53

TABLE IV. OBSERVED AND CALCULATED
EXTINCTION COEFFICIENTS

DATE	BAND								z _{sun}
	4		5		6		7		
	<u>O.</u>	<u>C.</u>	<u>O.</u>	<u>C.</u>	<u>O.</u>	<u>C.</u>	<u>O.</u>	<u>C.</u>	
May 27	.284	.41	.231	.34	.167	.28	.125	.11	33.7
June 5	.228	.38	.184	.18	.138	.18	.117	---	36.9
June 14	.668	.92	.557	.76	.445	.80	.398	.49	32.7
August 25	.275	.39	.211	.37	.167	.30	.152	.10	43.6
September 12	.285	.81	.228	.90	.182	.85	.186	.48	48.8
September 30	.146	.16	.104	.32	.067	.22	.064	.04	54.3
Average of 6 dates	.31±.18		.25±.16		.19±.13		.17±.12		
Standard Atmosphere	.331		.252		.217		.166		
O. = Observed C. = Calculated									

TABLE V. MEAN BACKGROUND ALBEDOS

	BAND			
	4	5	6	7
ρ	.100±.013	.079±.007	.207±.010	.245±.043

TABLE VI. MEAN LAKE REFLECTANCES AND STANDARD
DEVIATIONS

DATE	BAND			
	4	5	6	7
May 27	.0049±.0004	.0039±.0008	.0020±.0007	.0011±.0006
June 14	.0065±.0010	.0048±.0007	.0032±.0010	.0024±.0007
September 12	.0041±.0005	.0024±.0004	.0014±.0005	.0011±.0004

TABLE VII. AIRBORNE AND BOAT-BASED LAKE RADIANCES
(mw/cm²str)

AIRCRAFT OBSERVATION				
DATE	BAND			
	4	5	6	7
May 27	.0493	.0324	.0140	.0156
June 14	.0804	.0484	.0346	.0411
September 12	.0357	.0171	.0072	.0063
BOAT OBSERVATIONS				
May 27	.0434	.0294	.0188	.0320
June 14	.0809	.0755	.0382	.0706
August 25	.0422	.0256	.0084	.0077
September 12	.0312	.0203	.0090	.0186
September 30	.0231	.0139	.0053	.0086
CALCULATED LAKE RADIANCES				
June 5	.0367	.0248	.0114	.0172
August 25*	.0380	.0227	.0070	.0164
September 30*	.0205	.0120	.0042	.0072

* Calculated from boat observations using linear regression fit to May 27, June 14, and September 12th data.

TABLE VIII. WATER VOLUME REFLECTANCES

DATE	BAND			
	4	5	6	7
May 27	.0011	.0010	.00029	.00006
June 14	.0013	.0008	.00024	0
June 23	.0012	.0009	.00016	0
August 25	.0017	.0009	.00025	0
September 12	.0017	.0010	.00032	.00006
September 30	.0018	.0011	.00029	.00016
Average of 6 dates	.0015±.0003	.0010±.0001	.00026±.00006	.00005±.00006

TABLE IX. EXPECTED SUNGLINT RADIANCES

DATE	SOLAR ALTITUDE	WIND SPEED m/sec	r _g	L _g mw/cm ² str			
				4	5	6	6
May 27	56.3	3.6	.0012	.0511	.0138	.0128	.0257
June 14	57.4	3.2	.0015	.0120	.0117	.0110	.0233
September 12	41.2	0.7	<10 ⁻⁴	0	0	0	0

TABLE X. OTTAWA WIND AVERAGE SPEED AND DIRECTION
(speed in m/sec)

MONTH	1974	1975	1976	40 Yr. Av.
May	3.8 W	3.0 S	3.6 SW	4.4 SW
June	3.7 S	3.3 S	2.1 SSW	3.9 SW
July	3.7 SW	2.8 SW	2.5 SW	4.1 SW
August	2.7 S	2.5 W	3.3 SW	4.0 SW
September	3.2 S	3.4 W	3.2 W	3.8 SW
October	3.9 W	4.0 NW	4.1 WNW	4.2 SW

TABLE XI. LANDSAT RADIANCES OVER CLEAR LAKES
(mw/cm²str)

DATE	BAND			
	4	5	6	7
May 27	.340±.008	.189±.003	.158±.004	.139±.003
June 5	.312±.006	.141±.003	.106±.003	.183±.007
June 14	.510±.010	.293±.010	.334±.018	.488±.038
August 25	.277±.003	.166±.003	.132±.005	.120±.007
September 12	.330±.010	.214±.010	.219±.012	.339±.030
September 30	.204±.007	.127±.002	.091±.003	.056±.005

TABLE XII. OBSERVED AND CALCULATED PATH RADIANCES
(mw/cm²str)

DATE	4		5		BAND 6		7	
	O.	C.	O.	C.	O.	C.	O.	C.
May 27	.303	.281	.164	.146	.146	.105	.125	.153
June 5	.283	.252	.120	.127	.097	.089	---	.139
June 14	.469	.411	.266	.237	.312	.211	.461	.401
August 25	.248	.236	.147	.118	.126	.089	.106	.153
September 12	.303	.218	.201	.111	.213	.085	.334	.163
September 30	.186	.188	.116	.088	.087	.047	.049	.066

O. = Observed

C. = Calculated

TABLE XIII. LINEAR REGRESSION RESULTS

LANDSAT BAND	NUMBER OF POINTS	DEPENDENT VARIABLE	SLOPE MEAN ERROR		INDEPENDENT VARIABLE	INTERCEPT MEAN ERROR		CORRELATION COEFFICIENT
4	5	Calculated Path	.793	.025	Observed Path	.038	.008	.997
5	5		.895	.133		-.002	.023	.938
6	5		.656	.079		.007	.014	.958
7	4		.768	.069		.051	.017	.984
4-6	15		.886	.062		-.006	.014	.940
4-7	19	Radiance	.831	.054	Radiance	.012	.013	.933
Avg. of 4-6	5		.881	.043		.000	.009	.993
Avg. of 4-7	4		.791	.041		.019	.009	.995
4	5	Estimated Extinction	1.377	.110	Observed Extinction	.011	.040	.981
5	5		1.146	.283		.099	.085	.845
6	5		1.698	.237		.022	.056	.945
7	4		1.388	.131		-.071	.029	.983
4-6	15		1.317	.121		.060	.037	.902
4-7	19	Coefficient	1.269	.214	Coefficient	.061	.070	.729
Avg. of 4-6	5		1.404	.109		.038	.033	.982
Avg. of 4-7	4		1.381	.088		.027	.026	.992

TABLE XIV. ERRORS IN ATMOSPHERIC ESTIMATION

LINE	QUANTITY	BAND			
		4	5	6	7
1	δL_{sat}	.007	.006	.006	.015
2	r_{vol}	.0015	.0010	.00026	.00005
3	δr_{vol}	.0003	.0001	.00006	.00006
4	r_{surf}	.02	.02	.02	.02
5	δr_{surf}	0	0	0	0
6	r_g	.0023	.0023	.0023	.0023
7	δr_g	.0026	.0026	.0026	.0026
8	H_{tot}	14.42	12.66	10.54	21.33
9	δH_{tot}	.09	.09	.05	.07
10	H_{sun}	12.00	11.36	9.70	19.90

TABLE XIV. CONTINUED

LINE	QUANTITY	BAND			
		4	5	6	7
11	δH_{sun}	2.25	2.05	1.75	2.42
12	H_{sky}	4.00	2.83	2.10	3.70
13	δH_{sky}	2.24	2.10	1.20	2.01
14	τ	.331	.252	.217	.166
15	$\delta \tau$	.18	.16	.13	.12
16	L_{lake}	.049	.032	.014	.005
17*	$(\delta L_{\text{sat}})^2$	49.0	36.0	36.0	225.
18*	$(r_{\text{vol}} \delta H_{\text{tot}})^2$	.018	.0081	0	0
19*	$(H_{\text{tot}} \delta r_{\text{vol}})^2$	18.7	1.60	0.40	1.64
20*	$\left(\frac{r_{\text{surf}} \delta H_{\text{sky}}}{\pi}\right)^2$	203.	179.	58.9	164.
21*	$\left(\frac{H_{\text{sky}} \delta r_{\text{surf}}}{\pi}\right)^2$	0	0	0	0
22*	$(r_g \delta H_{\text{sun}})^2$	26.8	22.2	16.2	31.0
23*	$(H_{\text{sun}} \delta r_g)^2$	973.	872.	636.	2680.
24*	$(L_{\text{lake}} \delta \tau)^2$	77.8	26.2	3.31	0.36
25	$\exp(-2\tau)$	.516	.604	.648	.717
26	δL_p including sunglint	.027	.027	.022	.048
27	δL_p excluding sunglint	.014	.013	.0087	.019
28	$\partial \tau_T / \partial L_p$	2.5	3.3	2.5	1.1
29	$\partial \tau / \partial \tau_T$	.71	.87	.59	.67
30	$\delta \tau$ including sunglint	.048	.078	.032	.035
31	$\delta \tau$ excluding sunglint	.025	.037	.013	.014

* Lines 17-24 have been multiplied by 10^6 .

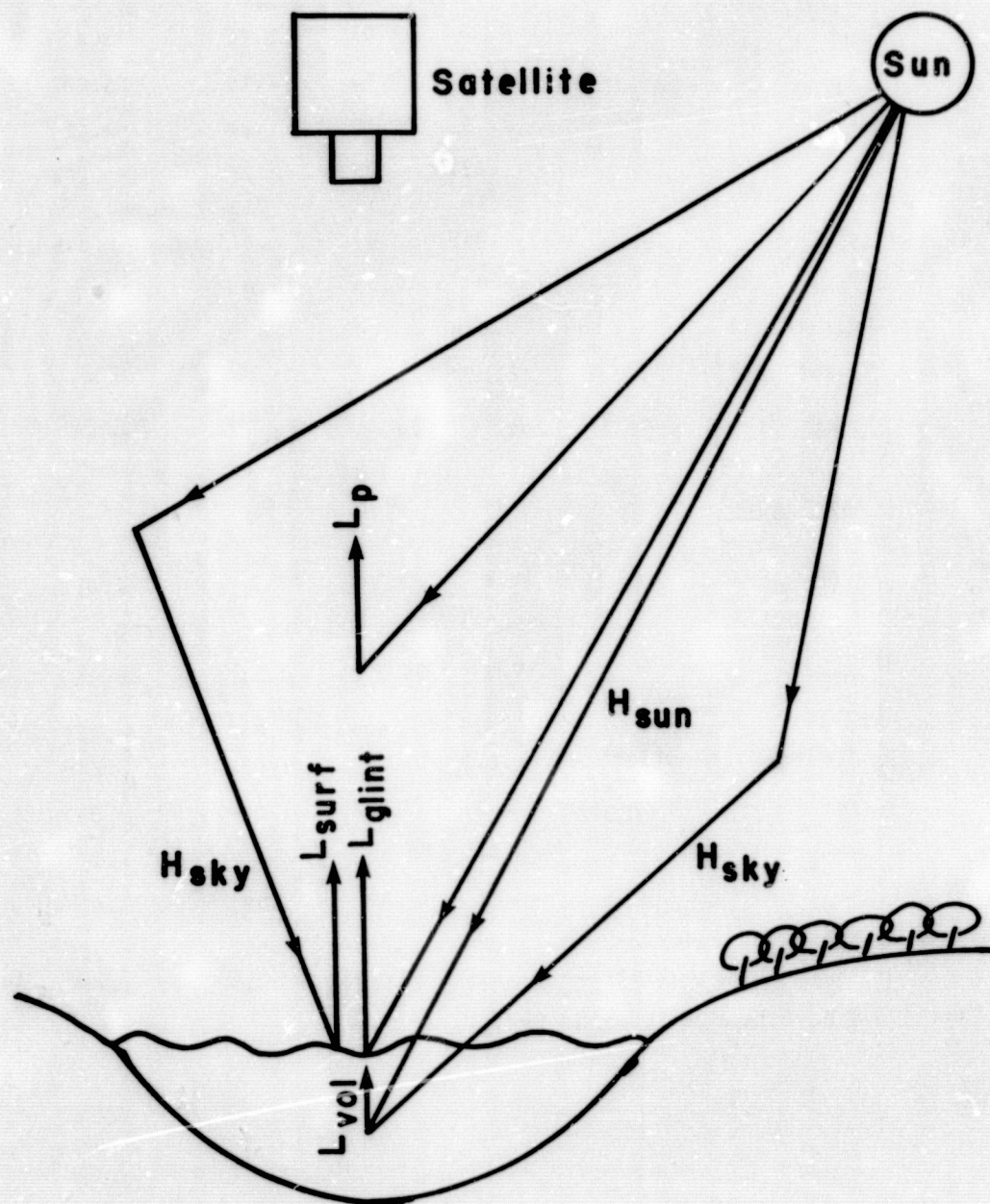


FIGURE 1. SCHEMATIC DIAGRAM OF RADIATION PROCESSES OVER A LAKE. Sunlight scattered by the earth's atmosphere can illuminate the lake (H_{sky}) and can be scattered to a satellite as path radiance (L_p). The radiance measured by the satellite $L_{sat} = (L_{vol} + L_{surf} + L_g)T + L_p$, where T is the atmospheric transmission.

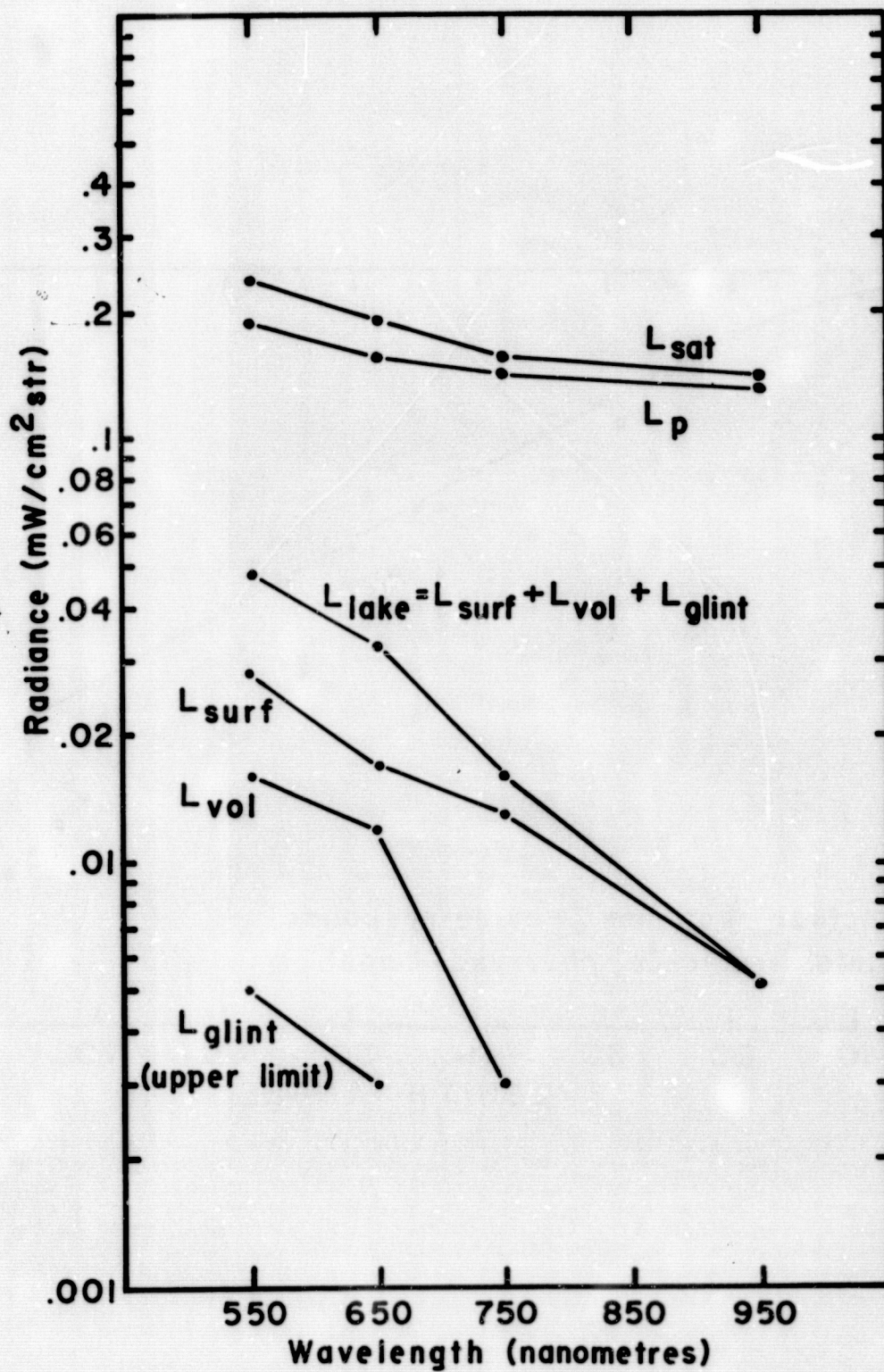


FIGURE 2. RELATIVE MAGNITUDES OF THE CONTRIBUTORS TO THE RADIANCE MEASURED BY A SATELLITE. Sunlint radiance may be much greater under high wind conditions.

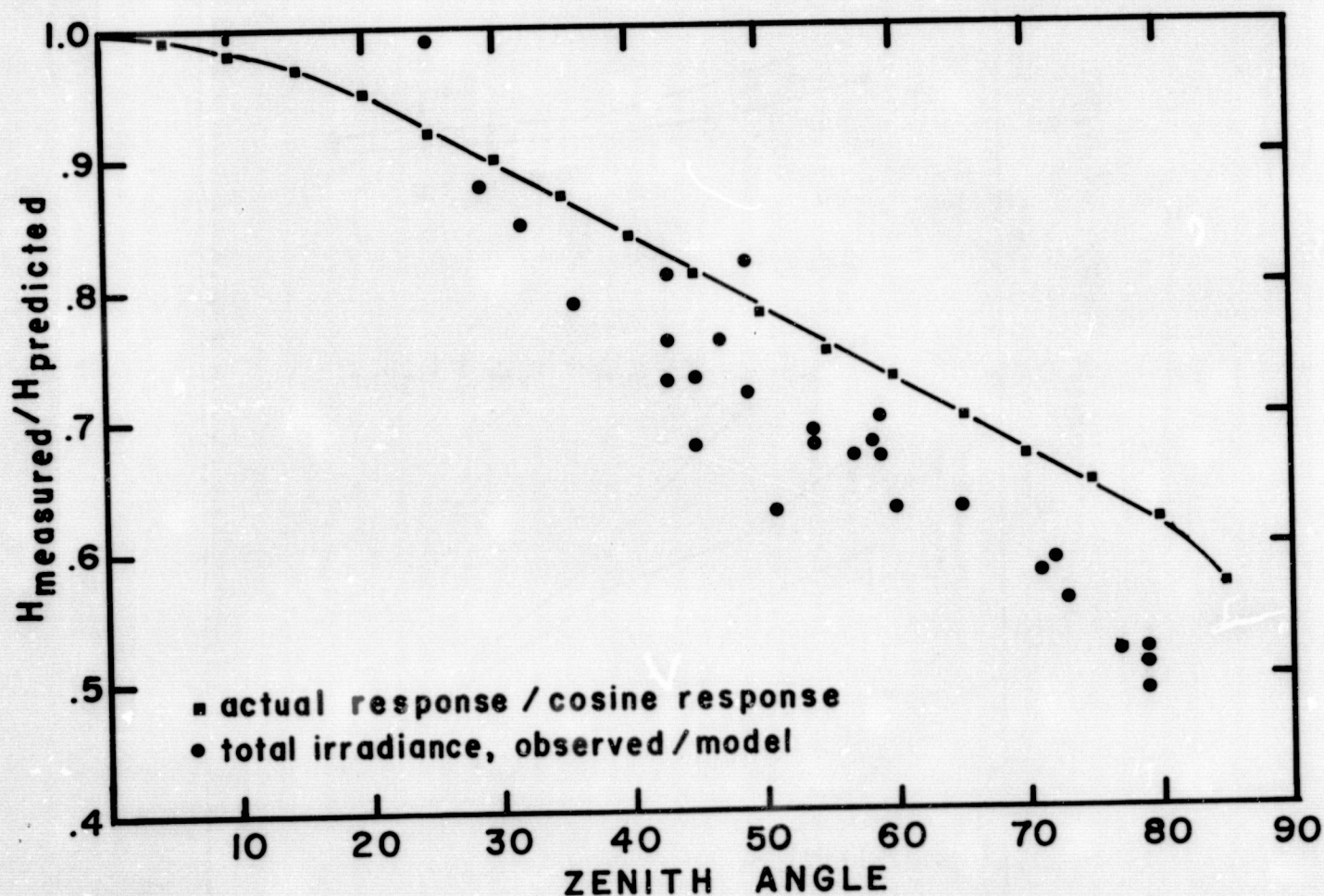


FIGURE 3. RATIO OF MEASURED TO PREDICTED RADIANCES. The squares represent the ratio of the signal from a constant point irradiance source at different "zenith" angles (measured relative to the optical axis of the RPMI) to the cosine of the zenith angle, which is the desired response. The circles represent the ratio of the observed total downwelling irradiance with the sun at different angles to the irradiance predicted by the Turner-Spencer (1972) model.

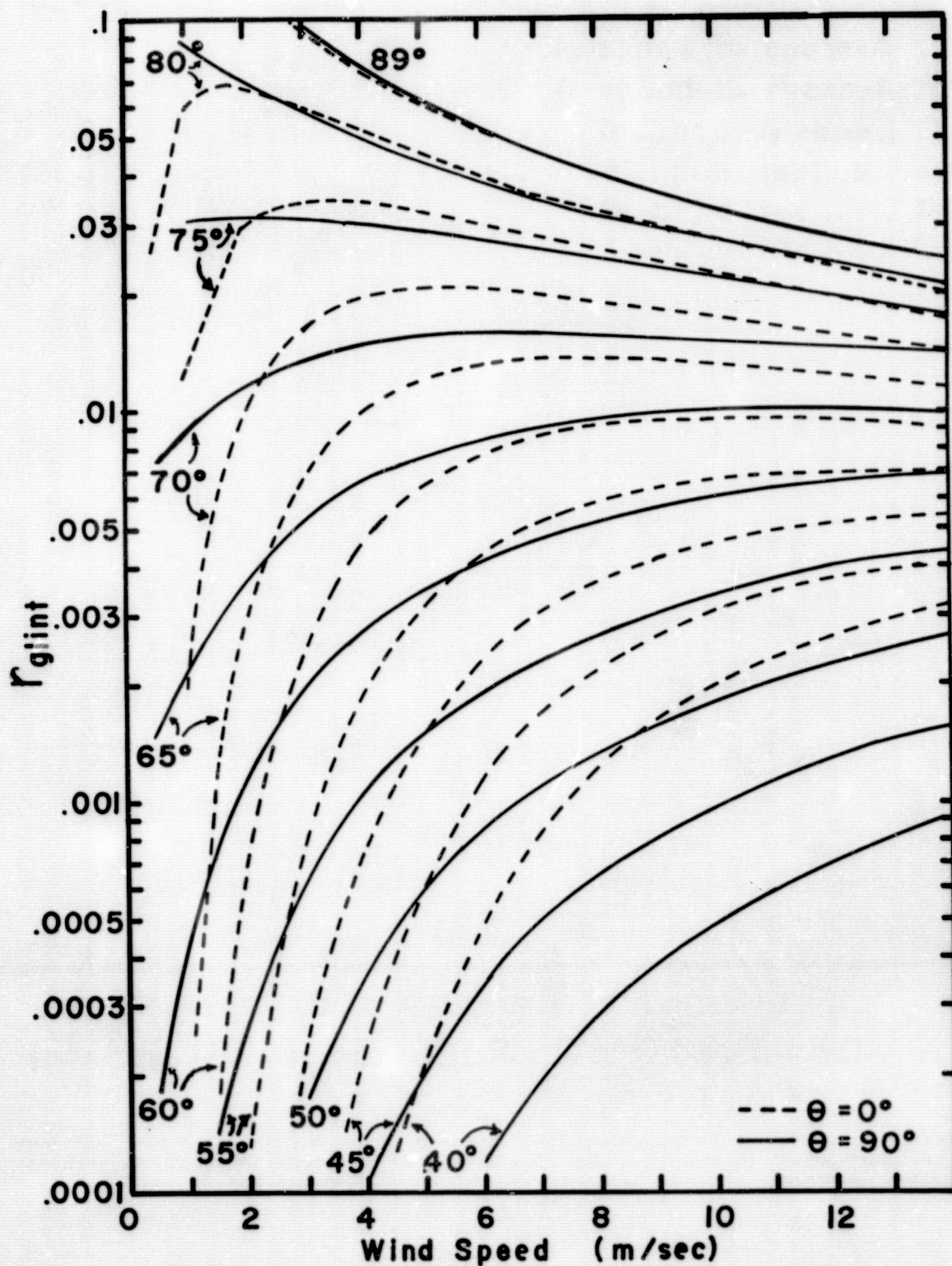


FIGURE 4. SUNGLINT REFLECTANCE. These curves have been calculated using the Cox-Munk (1954) model for a number of solar elevation angles (labeled). The two extreme cases of θ , the angle between the solar azimuth and the wind direction, are shown.

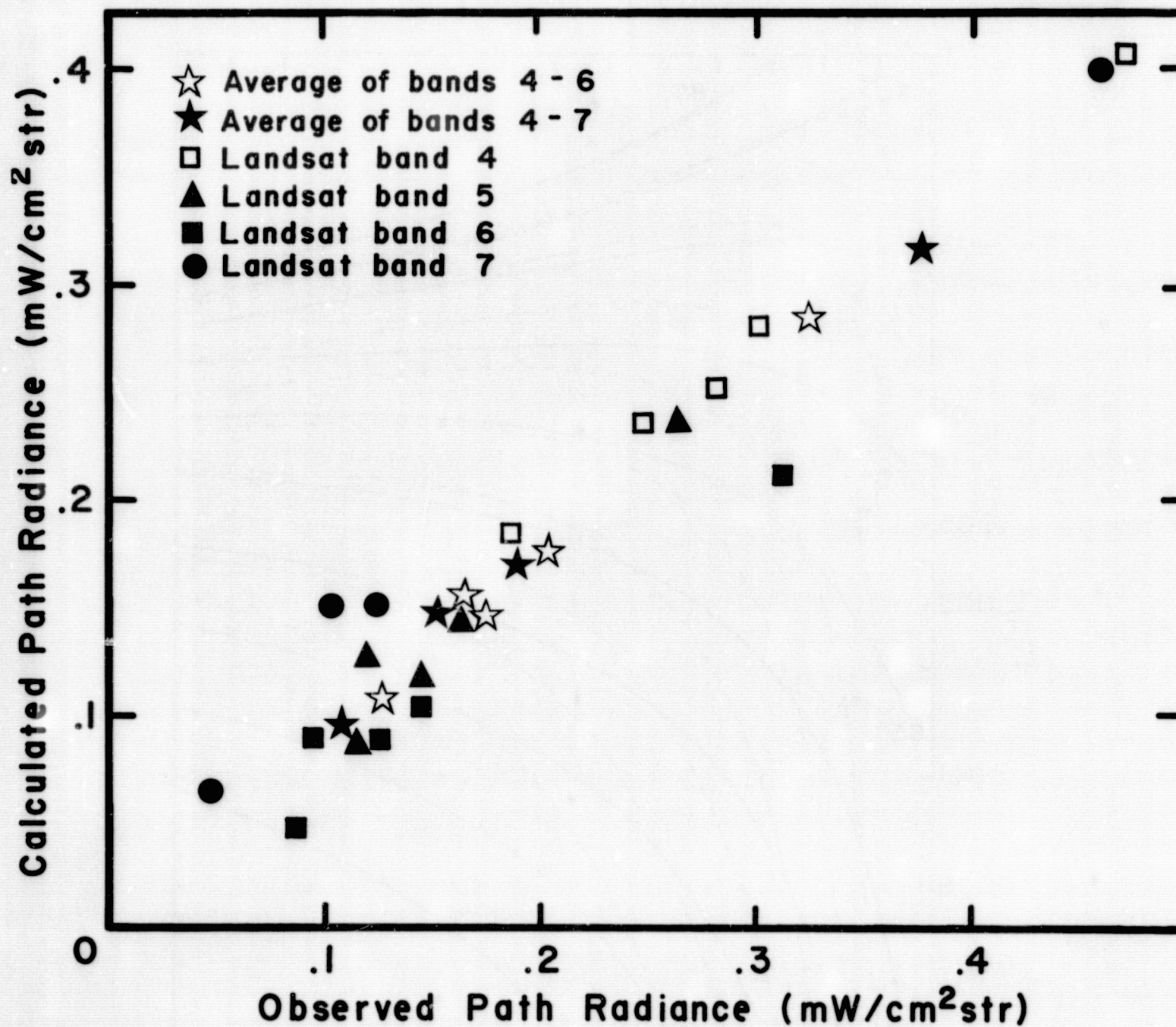


FIGURE 5. OBSERVED AND CALCULATED PATH RADIANCE. The observed path radiance is that measured by LANDSAT after subtracting lake radiance, and the calculated path radiance was determined using the Turner-Spencer (1972) atmospheric model with the extinction coefficient determined for each LANDSAT band by ground observations.

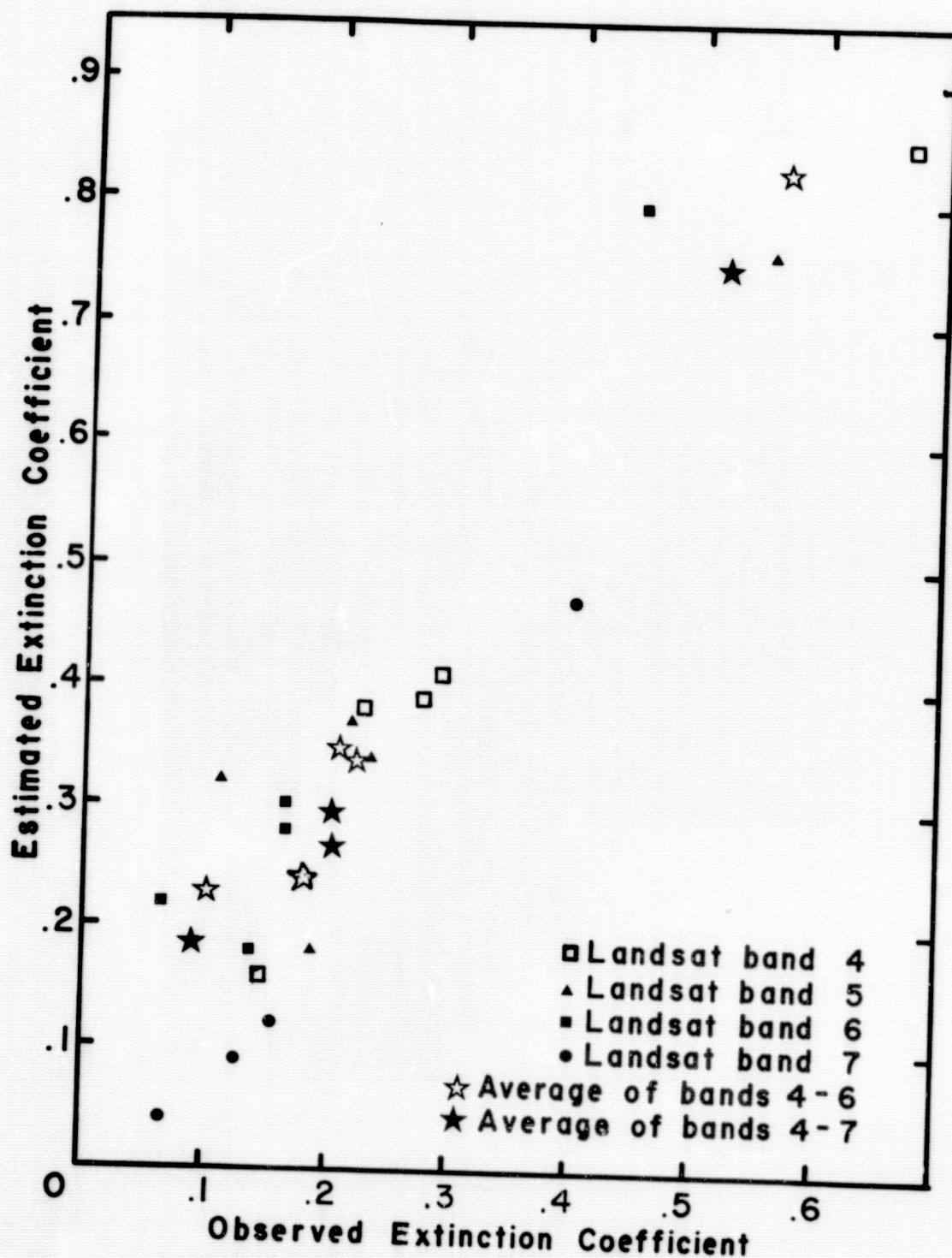


FIGURE 6. OBSERVED AND CALCULATED EXTINCTION COEFFICIENTS. The observed extinction coefficient is that measured for each LANDSAT band near the time of LANDSAT overpass. The calculated extinction coefficient was interpolated with the observed path radiance from a table of path radiances as a function of extinction calculated for the appropriate geometry for each date of observation using the Turner-Spencer (1972) model.

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A LOW-COST SYSTEM FOR RECEPTION AND PROCESSING OF LINE-SCAN

DATA FROM LANDSAT AND OTHER SOURCES

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1. INTRODUCTION

Over the past year and a half, much has been said at various seminars on the use of remote sensing, particularly as it pertains to the need for low-cost ground receiving stations and processing systems for data from remote sensing satellites. In addition, the need has been recognized for systems which will provide real-time information so that dynamic changes in phenomena observed by the satellites can be followed and acted upon. Over the past year a low-cost transportable earth resources ground station has been built in Canada and installed to operational status at Shoe Cove, Newfoundland. Figure 1.1 shows the station on its test site in Vancouver, B.C. We believe that the system concepts developed for this station provide an answer to the need for low-cost receiving and processing systems, providing timely availability of data in both photographic and digital form.

The system was designed with several objectives in mind: Firstly, to provide a system which could receive, store and process line-scan image data from a wide variety of satellites, most especially the LANDSAT and NOAA (VHRR) series, as well as aircraft scanner data, and data from future remote sensing and meteorological satellites such as METEOSAT, HCMM, NIMBUS-G, GMS, TIROS-N (AVHRR) and others; Secondly, the system has been designed to be operated by a small staff and to produce black and white images and computer-compatible tapes (CCT's) of all relevant data; Thirdly, the system is compact in its physical design so that it is possible to configure it as a self-contained ground station, housing all of the electronic equipment and a photographic facility in a 3 x 12 meter trailer; and finally, the system is designed to process all data at real-time rates or better and is designed in a modular fashion so that it can be easily upgraded to do further processing of the data, and/or to handle new satellites and sensors, and to accommodate technological change which affects the manner in which the data is handled, and the output products which are produced. At present, several configurations of the system exist or are under development. These range from ultra low-cost systems capable of handling data from only the low data-rate sensors such as VHRR, through low-cost LANDSAT compatible systems with limited processing capability, to systems capable of extensive electronic processing of the data. Since all the configurations are derived from the same basic system design and use the same modular components, they are "upwards compatible"; that is, a low-cost system can be upgraded later to have increased capability as the need arises. This approach allows potential users of such systems to customize the system to their particular needs at minimal cost, and to enter into the field without a large initial outlay of funds.

In the following sections, we first describe the basic system concept (Section 2). This is followed by a description of the Shoe Cove Station as well as other configurations of the system presently under development.

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2. THE SYSTEM CONCEPT

All remote sensing electronic imaging devices in operation today, or contemplated for the foreseeable future, can be characterized as being line-scan oriented. By this, it is meant that data is generated, transmitted and recorded on a sequential line by line basis. All of the multispectral scanners whether they are operating in spacecraft or aircraft, can be characterized in this fashion. Figure 2.1 shows the conceptual block diagram of the Line-Scan Readout and Processing System (LSRPS), which has been developed by MDA Ltd. to handle and process this class of data in digital form.

The first of these systems was supplied to the Canada Centre for Remote Sensing and is installed at Shoe Cove, Newfoundland. Other systems are presently under construction. The system is designed to handle data from LANDSAT, MSS AND RBV, NOAA VHRR, METEOSAT, VISSR, GMS and AIRBORNE MSS. Necessary additional subsystem components are presently being developed to handle data from TIROS-N, AVHRR, HCMM and NIMBUS, CZCS and the SEASAT-A Synthetic Aperture Radar (SAR).

The system concept can be broken down into six sections as shown in Figure 2.1. Each section consists of a set of individual functional units, each performing a unique function.

The particular functional units present in a given system and their capabilities and interconnection depend on the overall system objectives. As mentioned above, these may range from a simple station capable of receiving data and generating images from low data-rate instruments such as NOAA VHRR to a large configuration handling several satellites including LANDSAT with complete image processing, and enhancement capability.

The ANTENNA SECTION consists of a full autotracking, parabolic antenna. The size, type and hence cost of the antenna depends on the power and bandwidth of the signal being received, and upon the coverage circle desired given the orbital altitude of the satellite. For example, in the case of remote sensing satellites currently in orbit, LANDSAT imposes the most stringent conditions primarily because of the wide bandwidth required. LANDSAT has two operating power modes; high-power (20 watt) and low-power (10 watt). A 10 meter diameter solid dish will give a coverage radius of approximately 3200 km in high-power mode and 3000 km in low-power mode. A 6 meter dish on the other hand provides coverage radii of the order of 3000 km and 2700 km respectively. Below 6 meters, performance margins in the low-power mode rapidly become too low to ensure reliable performance. For operational LANDSAT use therefore, one is dealing with antennas in the 6 to 10 meter range depending on coverage. With antennas of this size, autotracking capability is an essential feature, and the maximum tracking and slew rates must be sufficient to accommodate the maximum angular rate of the satellite. The antenna receiving system consists of prime focus-mounted dual-band feeds covering the scientific and meteorological satellite bands (1650 to 1750 MHz (L-Band) and 2100 to 2200 MHz (S-Band)). The S-Band channel uses an uncooled temperature stabilized parametric amplifier, and the L-Band channel uses a low noise transistor amplifier.

The RECEIVER SECTION consists of the radio receivers and demodulators necessary to receive and demodulate the signals received from the various satellites that the station is designed to handle.

The units making up the PREPROCESSING SECTION of the system convert the signal format received from each of the satellites into a standard digital format which is common throughout the remainder of the system. At the output of each preprocessing unit the data from a specific line-scan instrument is presented in a standard digital format with the start-of-line, end-of-line, earth scan and calibration scan data clearly identified. This permits the system to be expanded to handle data from additional satellites or airborne systems by simply adding the appropriate preprocessing unit. In most cases, a High Density Digital Tape (HDDT) is placed at this point in the system to act as a bulk storage device for downlink data. The HDDT also generally serves as a means of high-density archival storage for the data.

The IMAGE PROCESSING SECTION receives data from a particular preprocessing unit, and performs the necessary operations on the data to create film images and computer compatible tapes as output products. The design philosophy behind this section of the LSRPS has been to create a universal system in terms of both data format and rate, to ensure that the system could be expandable enough to handle future as well as current image processing needs. This has been accomplished through the development of a series of flexible modular components controlled by a central computer. Since the individual system components store and process the data without actually passing it through the central computer, the system throughput is substantially higher than that normally realized using conventional computer processing. This results in a faster as well as more economic IMAGE DATA PROCESSING SYSTEM.

The three basic modules in the IMAGE PROCESSING SECTION consist of a memory system, and an IMAGE DATA PROCESSOR, as well as the control element which takes the form of a minicomputer or a microcomputer depending on the size and complexity of its task. The memory subsection consists of a high speed semiconductor memory which is combined in some cases with a high volume disk memory. The latter permits the storage of several complete scenes in randomly accessible form, and is used in those installations where more generalized processing of the data is implemented.

The IMAGE DATA PROCESSOR is responsible for radiometric correction and enhancement, geometric correction, and annotation of the data, as well as interfacing to the particular type of image recorder specified for the system. Geometric corrections performed on LANDSAT imagery, for example, consist of those which compensate for earth rotation, line length variations, mirror scan non-linearities, sensor offset, and panoramic distortion. All of these operations are carried on at real-time rates, making it possible to create film images directly as the satellite signal is being received. The result is a high quality product with the same availability as the well-known "Quicklook" imagery.

The OPERATOR INTERFACE SECTION consists of the necessary terminal devices that are required to allow the operator to control operation of the system. In those systems where the objective is to produce routine standard products, such as computer compatible tapes, and geometrically and radiometrically corrected film images, operator interaction takes place through a standard computer terminal. If, on the other hand, human interactive processing is required to perform such operations as image enhancement or classification, then, a more sophisticated interactive colour imaging display is necessary.

The OUTPUT PRODUCTS SECTION comprises the devices necessary to produce the system's output products. These consist of computer-compatible tapes (CCT's), film images, and raw data either in digital or facsimile format for instantaneous transmission to remote locations. The type of CCT transport used depends on the throughput desired for this output medium. Throughput rates range from 5 minutes per tape to 20 minutes per tape depending on the speed (and hence cost) of the CCT transport. In a similar way the requirements for throughput and image quality determine the type and cost of the image recorder employed to produce the film products. Good quality images can be obtained of a single spectral band at real-time LANDSAT rates using an image recorder based on a combination of a precision cathode ray tube and camera system. Higher throughput, and excellent image quality can be achieved by employing a high-speed laser-beam recorder, but at a considerable increase in cost. On the other hand, excellent image quality can be achieved at lower cost with a sacrifice in throughput rate by using a drum recorder of the type employed for the reception of high quality facsimile pictures. LSRPS systems have been supplied using each of these recording systems.

3. THE SHOE COVE STATION

As mentioned earlier, The Canadian Government has installed a second LANDSAT receiving station in Shoe Cove, Newfoundland. This station supplements the coverage of the first station at Prince Albert, Saskatchewan, resulting

in complete coverage of Canada's territory. The design of this station uses the LSRPS concept described above. It receives, stores and processes line-scan imagery from the LANDSAT MSS and NOAA VHRR instruments, is operated by a small staff; and is self-contained, housing all of the electronic equipment and a photographic facility in a 12 x 3 meter trailer. The system produces black and white images and CCT's as output products on a daily basis, and has the capability for direct facsimile transmission.

An outside view of the complete station appears in Figure 1.1. Figure 3.1 shows a layout drawing of the trailer. The electronic system for reception, storage and processing of the data is located in the left of the trailer. The right end contains a photographic darkroom and the air conditioner, washroom and storage area are located in the center. Figures 3.2 and 3.3 show the electronic equipment, and Figure 3.4 is a view of the photographic facility. The antenna in this particular installation is a precision 10 meter parabolic dish. Figure 3.5 shows a block diagram of the data handling system.

Referring to Figure 3.5, data is received from the satellite by the antenna and passed on to one or both of the two receivers. In the case of LANDSAT, the digital data stream is picked up by the wideband MSS receiver and passed through a bit synchronizer to the MSS FORMAT SYNCHRONIZER. At the same time, the multifunction receiver receives the tracking signal and drives the autotrack system for the antenna.

When the station is being used to receive NOAA VHRR data, only the multifunction receiver is used. In this case, the VHRR data is demodulated from a subcarrier to feed the VHRR DIGITIZER. The multi-function receiver also supplies the autotrack signals.

Both the MSS FORMAT SYNC, and the VHRR DIGITIZER feed their outputs into the central part of the data handling system through a bus switch. The role of these two units is to convert the downlink formats from the satellites into an essentially standard line-scan format suitable for being handled by the rest of the system. The bus switch selects the output from the appropriate unit, depending on the satellite data being processed, and feeds the data to the BUFFER MEMORY. This memory is microprocessor controlled, and is designed to double-buffer the data at high speed. It contains two 96 kilobyte buffers and is capable of handling data at rates in excess of 15 megabits per second. This data is reformatted and demultiplexed by the microprograms which control the BUFFER MEMORY. The data emerging from the BUFFER MEMORY is identical in format regardless of the source of the data. The microprograms which accomplish this standardization are downloaded to the BUFFER MEMORY microcontroller from the minicomputer which acts as the system control element. The data from the BUFFER MEMORY can be directed to three possible destinations through the high-speed output port, namely the BULK TAPE SYSTEM, the DISK STORAGE SYSTEM, and the IMAGE RECORDER via the IMAGE DATA FORMATTER. During normal operation, when data is being received from a satellite, it is routed via the BUFFER MEMORY to the BULK TAPE, and simultaneously an image is made by the IMAGE RECORDER. The IMAGE RECORDER, which is shown at the extreme left in Figure 3.2 consists of a precision CRT and Camera system.

The BULK TAPE SYSTEM (HDDT) used in this particular installation is unconventional. It uses a helical-scan video tape recorder to store the data. This recorder achieves a density of 1.55×10^5 bits/sq. cm and a continuous input bit-rate of 7.5 megabits/second. This is compatible with storing LANDSAT image data since, although the downlink data rate is 15 Mb/sec, the duty cycle is less than one-half. The system takes advantage of this to allow the use of a smaller tape recorder which achieves high tape density. In practice, it has been found that a whole day's data can be stored on one 20 cm diameter reel of 2.5 cm video tape. This tape recording technique will undergo operational testing at the Shoe Cove Station during the next year, to test its suitability for long term operational use. Successful completion of these tests are expected to result in considerable savings in operational costs mainly through lower tape costs and maintenance costs.

The IMAGE DATA FORMATTER (IDF) is responsible for applying all radio-

metric and geometric corrections to the data prior to recording the image on film. The radiometric corrections are accomplished by means of a look-up table (LUT), hence any arbitrary radiometric transfer function can be imposed on the data. The geometric corrections applied correct for panoramic (S-Bend) distortion, non-linear scan, variabilities in scanning speed, and sensor offset. All of these are properties of the scanning instrument itself. In addition, the IDF corrects the image for earth rotation. Thus the image produced is a map-like reproduction of the geographic features observed by the satellite. Data which controls the radiometric and geometric corrections applied to the data by the IDF is fed to it by the minicomputer on a scan by scan basis. The calculations which determine these corrections are carried out in real-time by the computer, based on data extracted from the signal by the FORMAT SYNCHRONIZER (or VHRR DIGITIZER) and the BUFFER MEMORY, as well as precomputed orbital data. The IDF also annotates the image with a grey scale and alphanumeric data provided by the minicomputer.

After data has been recorded by the BULK TAPE SYSTEM, it can be played back at real-time rates to make further imagery or to store the data on the DISK STORAGE SYSTEM. This unit consists of two 40-megabyte disks capable of storing up to two complete LANDSAT scenes of data or the equivalent. The DISK SYSTEM also handles data at up to real-time rates. This system works in conjunction with the BUFFER MEMORY to provide a general purpose image manipulation capability. This is facilitated by the presence of a third port on the BUFFER MEMORY which connects it to the minicomputer. This port is bidirectional, and is arranged such that the BUFFER MEMORY appears to the minicomputer as an extension of its own memory system. Thus the computer system has a total memory in excess of 256K Bytes.

The principle role of the minicomputer is to act as a control element for the system. In performing this task, the computer communicates with the system operator through a CRT terminal which is built into the main control console, and controls the status and information flow within the rest of the system by means of control interfaces with each of the system components. In addition to the main control function, the computer handles data in the making of CCT's and the sending of imagery over a facsimile network. In both of these operations, an image is dumped onto the DISK STORAGE SYSTEM from the BULK TAPE and then fed through the minicomputer to the CCT transport or facsimile interface, as the case may be, at a rate controlled by the latter unit. In the case of CCT's, the throughput is determined by the CCT transport used, and formatting of the data is controlled by the minicomputer. A new image can be transferred from BULK TAPE to DISK in the time it takes to change a tape on the CCT transport. In the case of facsimile transmission, filtering of the data is performed by the minicomputer to achieve an optimum performance consistent with the bandwidth of the facsimile network and the resolution of which that system is capable.

Receiving and preprocessing software currently implemented on the system consists of programs to perform orbital calculations from given orbital parameters, to acquire, store and image data directly from satellite passes, to make imagery and CCT's from prerecorded data and to transmit images to remote sites via facsimile. These programs all operate in an interactive mode with the operator, under the control of a real-time operating system. Figures 3.6 and 3.7 are examples of imagery produced by this station. Figure 3.6 shows a NOAA VHRR image of north western Canada taken on March 19, 1976. Great Bear Lake, Great Slave Lake, and Lake Athabaska can be clearly seen. Figure 3.7 is a LANDSAT MSS image of the Peace River where it connects with the western end of Lake Athabaska. This much higher resolution picture was also obtained on March 19, 1976 within 18 minutes of the NOAA image of Figure 3.6. Some of the features shown in the LANDSAT image (Figure 3.7) are clearly visible in Figure 3.6.

A precision image analysis software package has been developed for use on larger LSRPS configurations. This software package is an interactive multiuser system designed specifically for the correction, registration and classification of line-scan imagery. Taking advantage of the latest developments in precision radiometric and geometric registration procedures, the system is

capable of multitemporal as well as multispectral classification. Both supervised and unsupervised classification procedures on either rectified or unrectified imagery are available to the analyst, and complete operational flexibility allows the system to be used in a research or production mode.

Further activity in the development and installation of low-cost receiving and processing systems is being pursued in Canada. This includes an LSRPS system being built for the Prince Albert Satellite Station (PASS) to bring its data handling capability to the same level as the new Shoe Cove Station. The system being constructed for PASS is essentially the same as the one described above except that they already have much of the receiving and recording equipment and the output film products will be produced by a high-speed laser-beam image recorder. This will allow simultaneous production of full resolution images of all four LANDSAT spectral bands at real-time rates. The only change in the system design required to accommodate this film recorder was the replacement of the Image Data Formatter of Figure 3.5 with a more sophisticated Image Data Processor capable of handling the requirements of the Laser Beam Recorder relative to data rate and the necessary geometric correction algorithms.

In addition, a small very-low-cost satellite station is also being built for Canada's west coast which is directed exclusively at handling data from meteorological satellites. The system uses the LSRPS design concept with the same preprocessor and receiver modules. The Image Processor Section is simpler than is the case for LANDSAT compatible systems, because of the reduced requirements for data handling imposed by the meteorological satellites relative to those of LANDSAT. This has led to the design of a series of ultra-low-cost LSRPS systems capable of producing imagery and computer compatible tapes from low data-rate satellite sensors. At present the station is being equipped to handle the NOAA VHRR data, but will be expanded in the future to include TIROS-N, AVHRR and possibly some other satellites.

Figure 3.8 shows a block diagram of a family of low-cost meteorological receiving and processing systems, based on the development of the Canadian west coast station. Developments underway include preprocessors to handle HCM1, METEOSAT, GMS, and NIMBUS-G as well as AVHRR. The processor section has the capacity to perform radiometric enhancement, electronic enlargement, and geometric compensation for panoramic distortion, as well as film annotation, all at real-time rates.

4. CONCLUSIONS

This paper has summarized the developments which have taken place at MDA Ltd. over the past few years toward the development of a technical concept for low-cost receiving and processing systems for remote sensing satellite imagery. The result has been a highly flexible modular system, which can satisfy a wide spectrum of user needs and be flexible enough to accommodate changes in these needs and in the technology itself, while at the same time keeping the costs within reasonable limits. It produces high quality black and white imagery and computer compatible tapes right at the ground station, thus making the data available as rapidly as possible following the satellite pass. We believe that this concept of a low-cost ground station has the potential to satisfy many of the requirements for remote sensing data handling systems which presently exist around the world. Figure 3.9 shows a ground station and processing system for LANDSAT MSS and RBV, ITOS AVHRR, and AIRBORNE MSS.

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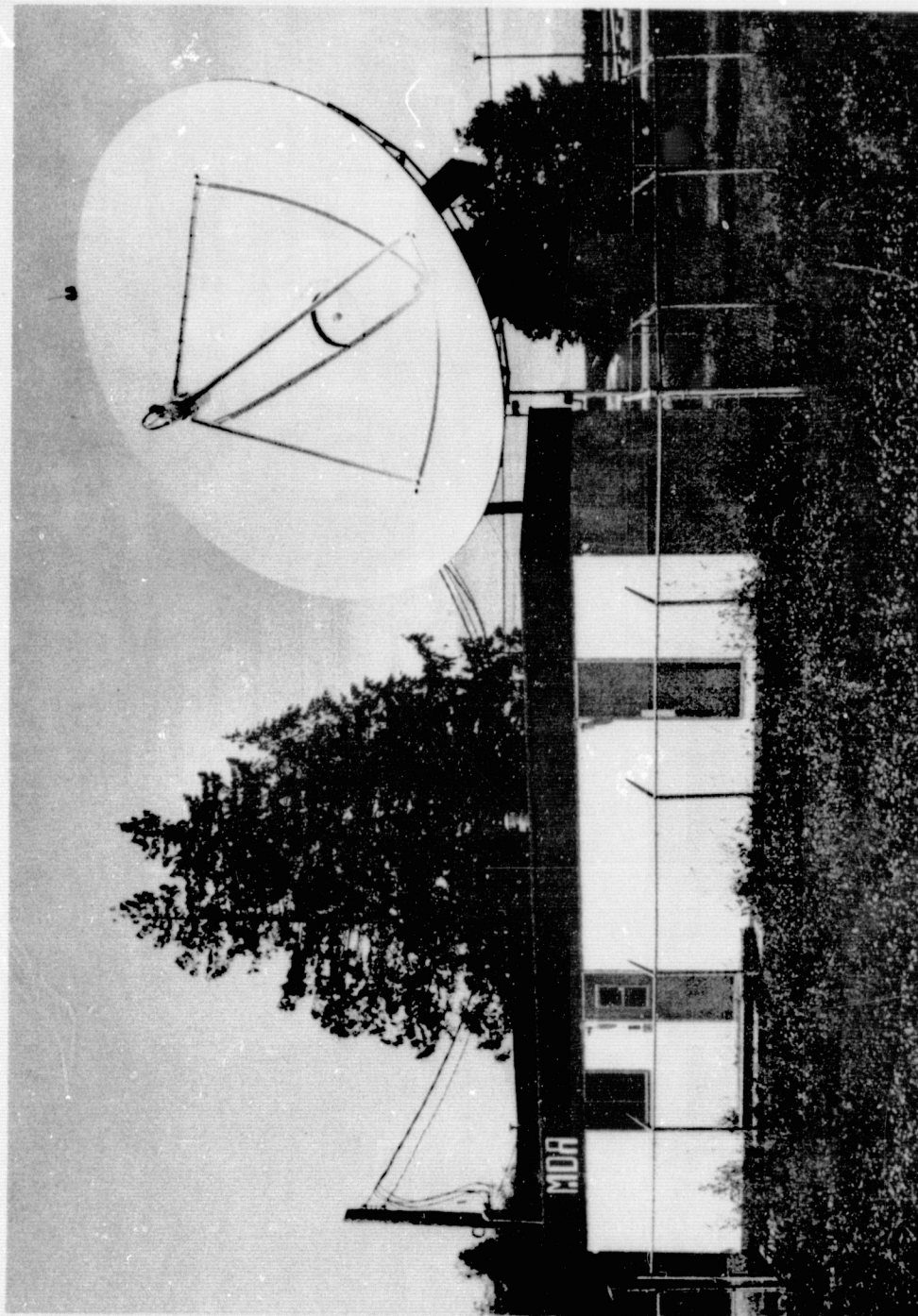


FIGURE 1.1

GROUND STATION

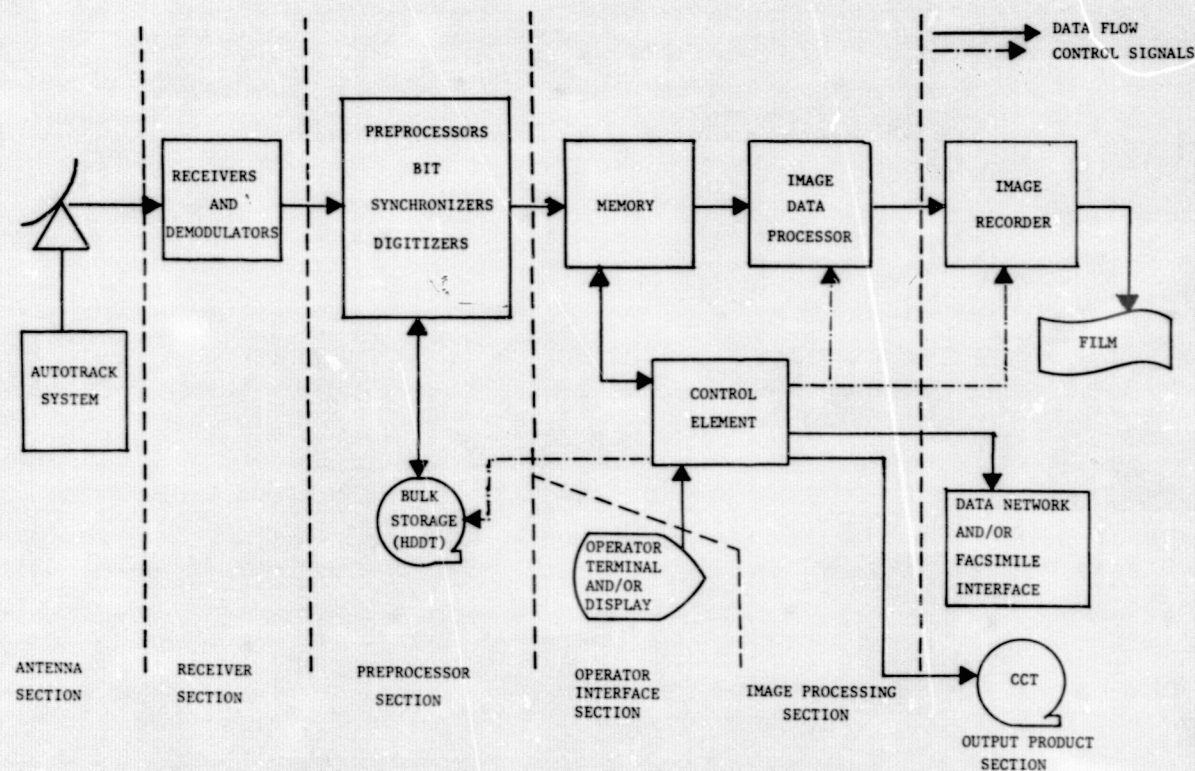
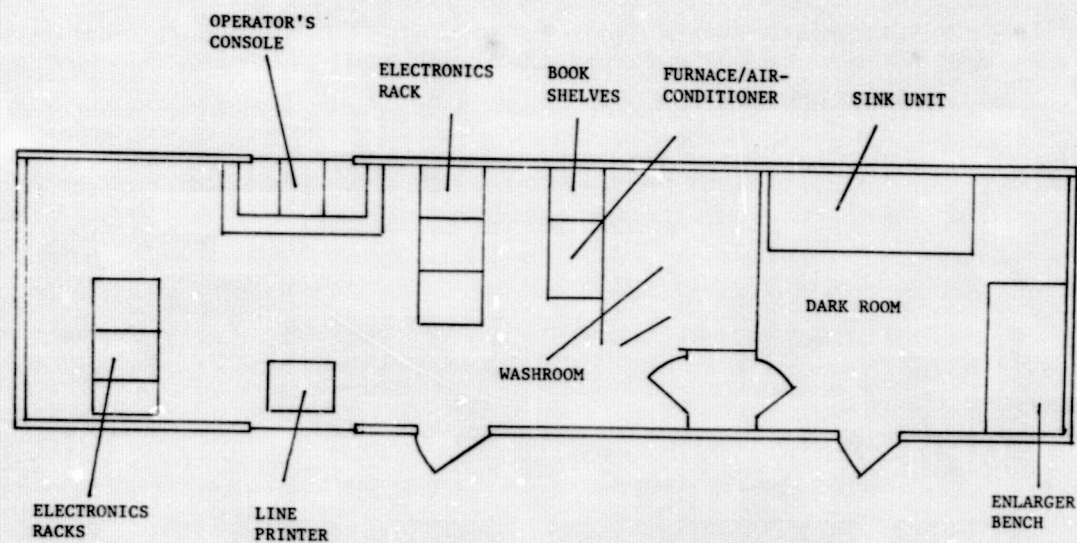


FIGURE 2.1 - LINESCAN READOUT AND PROCESSING SYSTEM (LSRPS) - CONCEPTUAL BLOCK DIAGRAM

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TRAILER LAYOUT
SHOE COVE STATION
FIGURE 3.1

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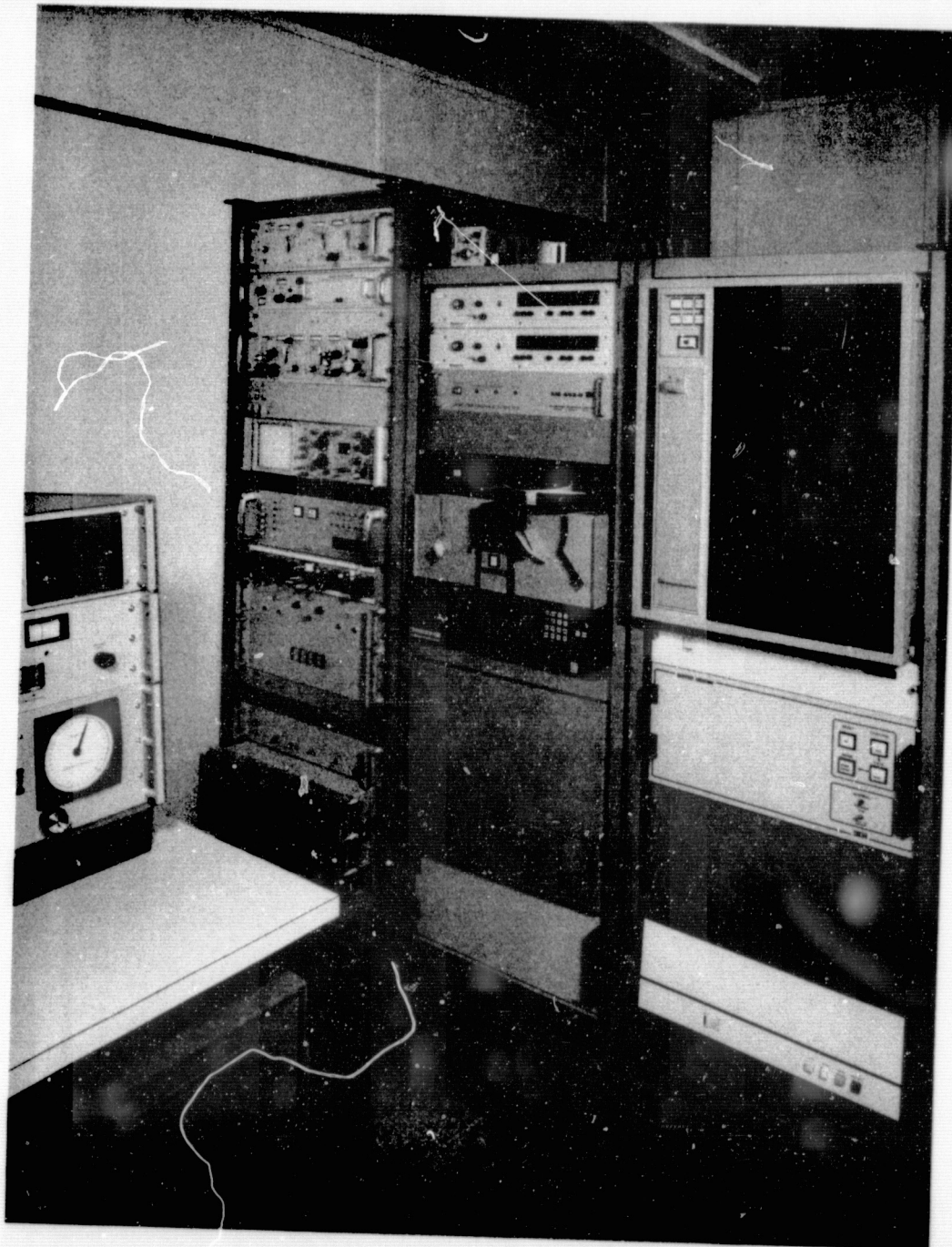


FIGURE 3.2
ELECTRONIC EQUIPMENT

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ELECTRONIC EQUIPMENT

FIGURE 3.3



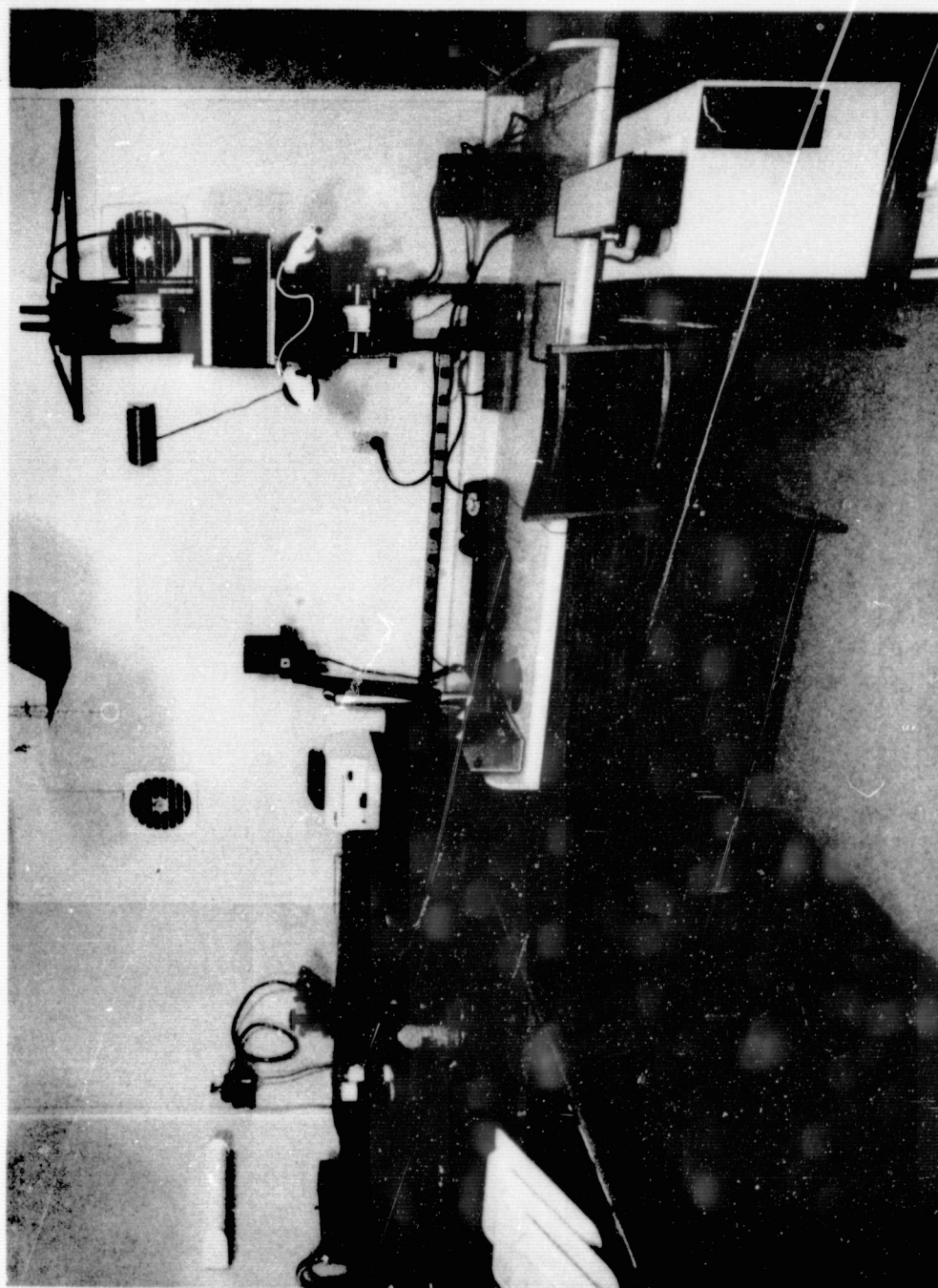


FIGURE 3.4

PHOTOGRAPHIC FACILITY

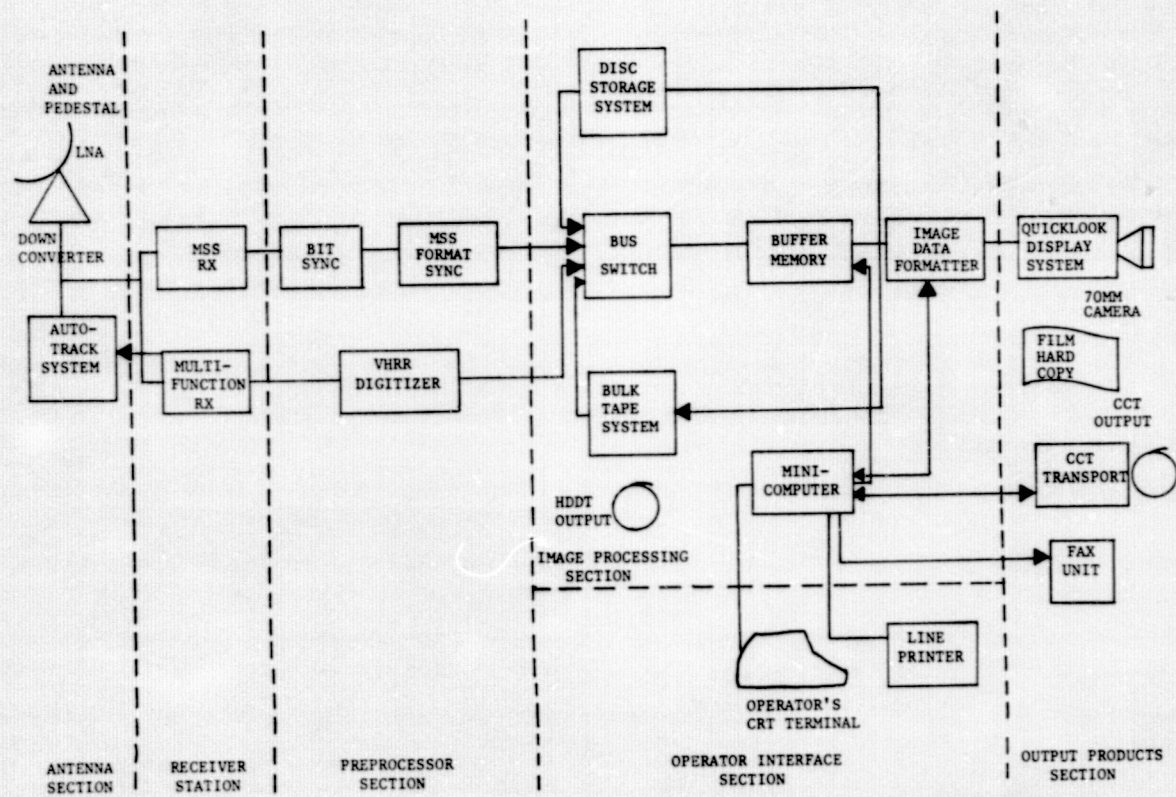


FIGURE 3.5 - DATA HANDLING SYSTEM

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NOAA VHRR IMAGE

FIGURE 3.6

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FIGURE 3.7

LANDSAT MSS IMAGE

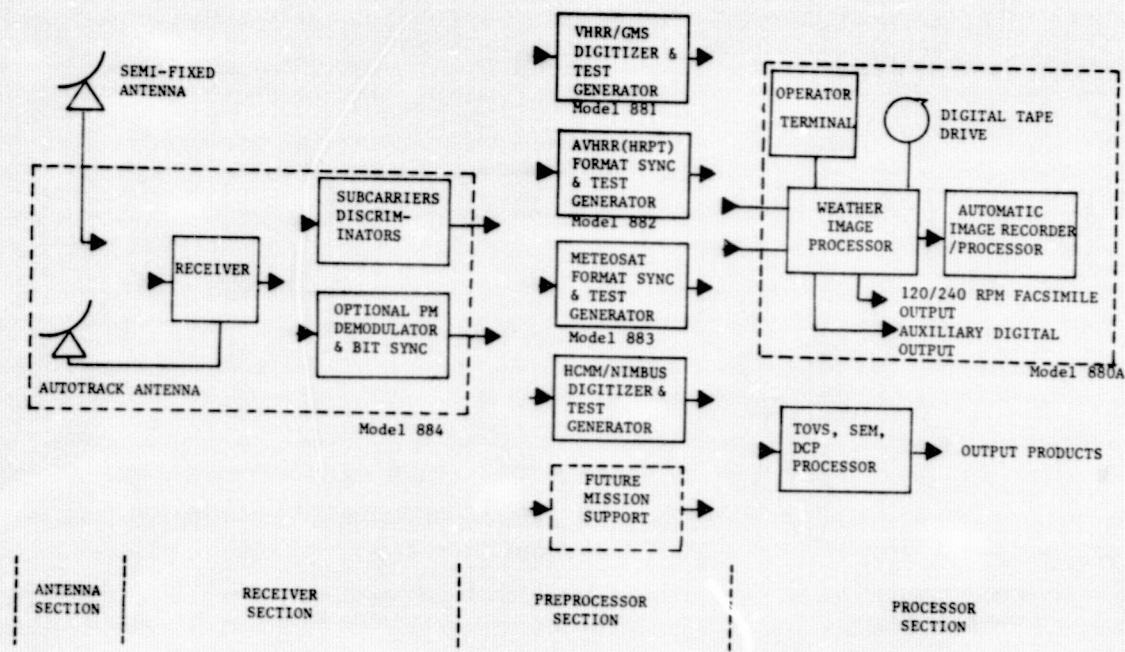
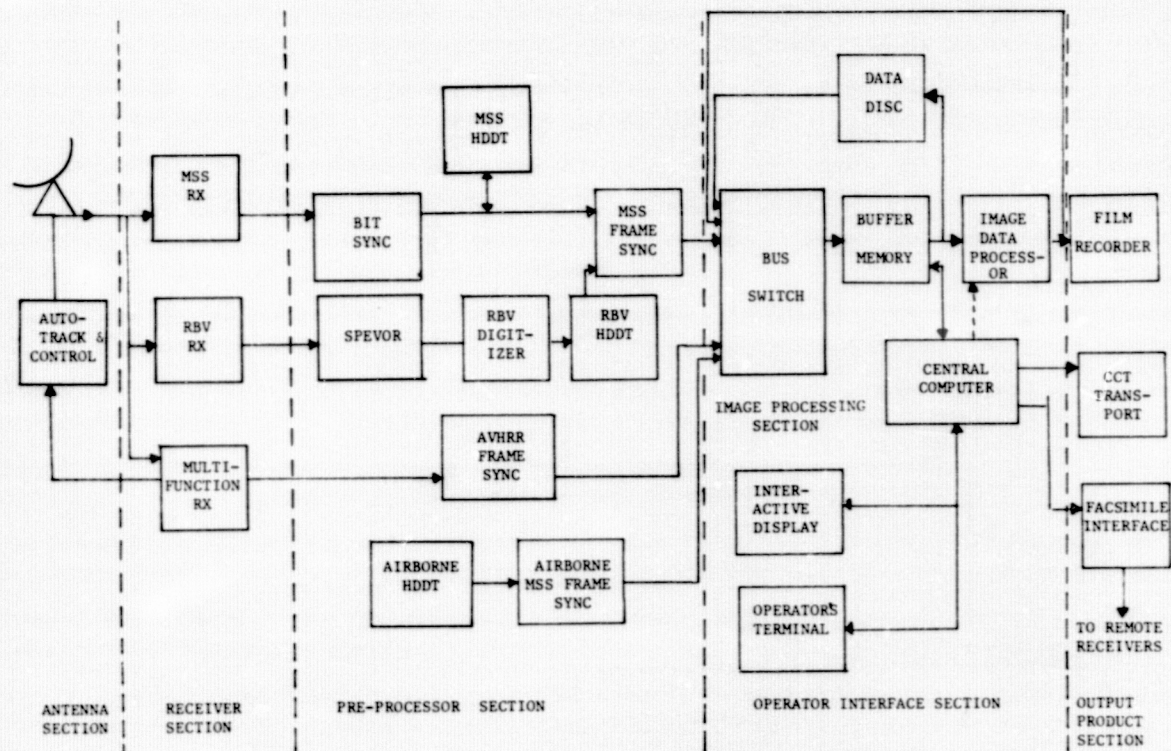


FIGURE 3.8 METEOROLOGICAL DATA SYSTEMS - BLOCK DIAGRAM



GROUND STATION AND PROCESSING SYSTEM FOR LANDSAT MSS AND RBV, ITOS, AVHRR AND AIRBORNE MSS

FIGURE 3.9

D60
N78-14524

THE USE OF LANDSAT IMAGERY
TO LOCATE UNCHARTED COASTAL FEATURES
ON THE LABRADOR COAST

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ABSTRACT

In 1976 the Atlantic Region of the Canadian Hydrographic Service carried out a survey of several offshore islands, rocks and shoals on the Labrador Coast. On this survey, for the first time, LANDSAT imagery was used to assist in the location of uncharted hydrographic features. Several satellite coverages of the coast were studied prior to the survey by Topographical Survey, EMR, and suspected shoal points identified. Using map-derived control points and monocomparator measurements of the LANDSAT images, the positions of these points were determined by mathematical adjustment to an estimated position accuracy of 150 metres. As a result, on the survey, an uncharted island and eight uncharted drying rocks, which might easily have escaped detection from a survey ship, were verified and positioned. To check the accuracy of the coordinates derived from LANDSAT, three islands were positioned by standard ground survey methods. The positional differences, all less than 150 metres, are not plottable at the scale of the existing offshore charts. The LANDSAT positions were also used to control aerial photography of a shoal area for office compilation of a hydrographic chart.

INTRODUCTION

In 1976, the Atlantic Region of the Canadian Hydrographic Service, with Headquarters at the Bedford Institute of Oceanography, Dartmouth, N.S., carried out a survey of several offshore islands, rocks and shoals on the Labrador Coast from Cape White Handkerchief to Cape Chidley.

The purpose of this project was to determine the positions and characteristics of these offshore points, which are so critical for safe navigation in these coastal waters. The survey was carried out by the CSS BAFFIN with D.D. Lelievre as Hydrographer-in-Charge.

The coast, from Cape White Handkerchief to Cape Chidley 120 km Northwest, is indented by five fiords along with numerous small inlets and bays and is more rugged and mountainous than the southern coast of Labrador. The Tornat mountains, rising between 600 and 1200 metres, parallel this part of the coast.

Offshore along this sector, there are numerous unsurveyed islands, isolated rocks and shoals extending offshore from distances of three to sixteen kilometres from the mainland. Vessels usually keep to seaward of the dangers, as the whole region has not been surveyed. Positioning these offshore features presents many problems. Detailed survey and positioning by ship or launch is possible, but rarely practical due to considerations of time and cost of survey

and ice in these northern coastal waters. Photogrammetric methods, using stereoscopic viewing of aerial photography, cannot be used if the water gap between the feature and mainland control is greater than one or two miles. A relatively new method of positioning, taking advantage of LANDSAT satellite coverage, has been developed, which shows promise of providing considerable assistance for plotting such features (1). This method was applied to the Labrador Coast.

PRE-DETERMINATION OF THE SHOAL POSITIONS BY PHOTOGRAMMETRY

Prior to the Hydrographic Survey of the Labrador Coast, LANDSAT images of the area were examined in the Topographical Survey Directorate of the Department of Energy, Mines and Resources. An inventory search at the Canada Centre for Remote Sensing had located eight images of the area obtained during relatively cloud-free, ice-free conditions. Offshore features, not plotted on current hydrographic charts, were observed on three of these images and positioning of these points proceeded using photogrammetric methods.

The three LANDSAT images used were from three different orbits, at three different dates:

<u>Image</u>	<u>Date</u>
13-18-43	August 23, 1974
14-18-25	October 4, 1973
15-18-62	August 2, 1975

The location of these images relative to the coastline is shown in Figure 1. Since the images on successive orbital paths have a high overlap it was possible to obtain two position readings for most shoal points. For one small group of shoals which fell in the common overlap of the three images, three independent positions were determined.

The segments of the LANDSAT images showing both the offshore features and the coastline were enlarged to make standard sized diapositives. This enlargement increased the observing scale from the original 1:3,369,000 scale of the LANDSAT 70mm frame to a scale of 1:400,000 on the diapositive. Control points were established on these diapositives by identification of image features on the mainland whose U.T.M. coordinates could be measured on the published 1:50,000 maps of the area. These features were well defined shoreline points or small lakes.

The control points and the offshore features to be positioned were marked on the diapositives by drilling 60 mm holes in the film emulsion with a Wild PUG-4 transfer device. Using a Wild Stereocomparator STK-1 in the monocular mode, the X and Y coordinates of the marked points were measured in each of the three image segments. These measurements were transformed to the U.T.M. coordinate system by an affine transformation and a least squares fit to the control points, and coordinates for the shoal points were thus determined.

The positions of the shoals determined from the measurements on the three images were supplied to the Hydrographic Service, together with 1:100,000 enlargements of the LANDSAT images showing the identifications of the points measured.

SOURCES OF ERROR IN THE PHOTOGRAMMETRIC DETERMINATION

One of the geometric distortions that may occur in LANDSAT imagery is a difference in scale between the image scan direction which is perpendicular to the orbital path, and the scale along the orbital track. The orientation of the coastline and the presence of cloud inland prevented the establishment of a good scale in the scan direction for the images. This factor, coupled with the fact that the control was based on map-derived coordinates of image points, resulted in position information that had a greater degree of uncertainty than that established for the Ungava shoals previously determined in 1975 (1). For the Labrador coast the R.M.S. error at photogrammetric control was 80 metres, and for the offshore shoal points for which three readings were obtained deviations from the mean varied from under 30 metres in northings to 155 metres in eastings.

The LANDSAT image at extreme enlargement has such poor image quality that defining a precise point is impossible. The offshore rocks and islands on the Labrador coast are much smaller than the resolution element of this system, so that what was seen and positioned was the white water surrounding these points, the centre of which would probably shift with wind direction. The five images on which offshore features could not be detected were probably obtained on relatively calm days.

FIELD OPERATION

The extent of the survey carried out by the CSS BAFFIN is shown in Figure 2. To assist in the location of the offshore features there were field sheets prepared from reproduction of the 1:50,000 topographic maps, aerial photographs taken in 1950 and the LANDSAT position information provided by Topographical Survey.

Horizontal control and shoal examinations were carried out by the BAFFIN launches and helicopter parties. Careful observations had to be made on the nature of the features because of the significance these features could have on the charting priorities for the area. The helicopter was used extensively for identifying shoals, rocks, islands and obtaining photographs and heights of rocks.

At the positions provided by the LANDSAT imagery, eight uncharted drying rocks and one uncharted island were verified and photographed. The other positions supplied represented already-charted points.

During the survey, three reported offshore shoal areas were examined by sounding launch. These included "Davidson Rock", a shoal area reported in 1950 and a "rock" reported seaward of the Galvano Islands. No indication of features in these areas had shown on the LANDSAT imagery. Soundings were done by launch, positioned by radar ranging from the BAFFIN. No shoals were found and least depths of 160 metres, 42 metres and 18.9 metres were determined in the areas.

COMPARISON OF LANDSAT POSITIONS WITH GROUND SURVEY POSITIONS

To assess the accuracy of the U.T.M. coordinates derived from LANDSAT, they were compared with those obtained from conventional horizontal control. The results for three surveyed points which were also measured on LANDSAT images are shown in Table 1. It can be seen that the positional differences

for these points varies from 10 metres to 140 metres in Northing and 42 to 91 metres in Easting. These positional differences, all less than 150 metres, are not plottable at the scale of the existing offshore charts.

OFFICE COMPILATION

The primary purpose of the survey was to examine the offshore hazards to navigation along the coastal boundaries. It was noted on the LANDSAT images that there were many more uncharted rocks and shoals in the area west of station SHOAL, eleven km. north of the Galvano Island group.

This was another example of an area where the offshore features were separated from the mainland control by water gaps in the aerial photographs and time could not be expended to carry out a complete survey of the islands and rocks.

On return to the Bedford Institute of Oceanography, office compilation of this shoal area was undertaken.

This area was never mapped at 1:250,000 in the topographic series. The rocks and shoals were carried on the existing charts by the notation "Numerous uncharted ledges and shoal ground". This shoal ground covered an area of approximately 50 square nautical miles.

The coordinates of all existing hydrographic control points and the coordinates of the rocks and shoals provided by LANDSAT positioning were plotted on the hydrographic field manuscript.

These control points were previously identified on aerial photographs covering the area from Galvano Islands northward to Home Islands. The points controlled by LANDSAT positioning were transferred to the aerial photos to provide more control for plotting.

With the use of a Saltzman projector and the conventional aerial photographs, the uncharted area was plotted on the existing field manuscript at the natural scale of 1:50,000. Approximately forty-three rocks and shoals were found to exist that were not previously charted. The exact position of these rocks and shoals is yet to be determined by a survey party, however the shoreline plot of the offshore rocks and shoals determined by aerial photographs and LANDSAT should provide the survey party returning to the area with a good provisional chart to plan and carry out precise surveys to position these hazards.

CONCLUSION

LANDSAT imagery is a valuable aid in detecting shoal areas and for positioning offshore islands and rocks where these areas are inaccessible from shore control stations and are beyond the range of conventional aerial photogrammetry. Because of its inherently poor resolution, the nature of the feature detected on the imagery can only be established by field survey or in some cases, by aerial photography. Used in conjunction with aerial photography, LANDSAT can provide position information for the many additional features that will show on the photography of shoal areas.

In northern waters the number of available images which are both ice-free and cloud-free is limited, but if several images of an area can be obtained then photogrammetric methods can provide position information that is good to 150 metres R.M.S. for features that are 16 kilometers or more from shoreline to control. This fact could prove useful for other surveys in marginally mapped coastline areas.

Reference:

- (1) Fleming, E.A., Positioning Offshore Features with the Aid of LANDSAT Imagery, Photogrammetric Engineering, January, 1977. Vol. XLIII No. 1.

TABLE 1
ACCURACY OF LANDSAT POSITIONING

POINT	DESCRIPTION	U.T.M. NORTHING (m)			U.T.M. EASTING (m)		
		SURVEY	LANDSAT	DIFF	SURVEY	LANDSAT	DIFF
Rock C	Small Island h=8.5m	6680958	6681098	140	432777	432832	55
Polar Rock	New Island h=6m	6671326	6671375	49	442138	442096	42
SHOAL STA.	Small Island h=13m	6660032	6660042	10	445042	445133	91

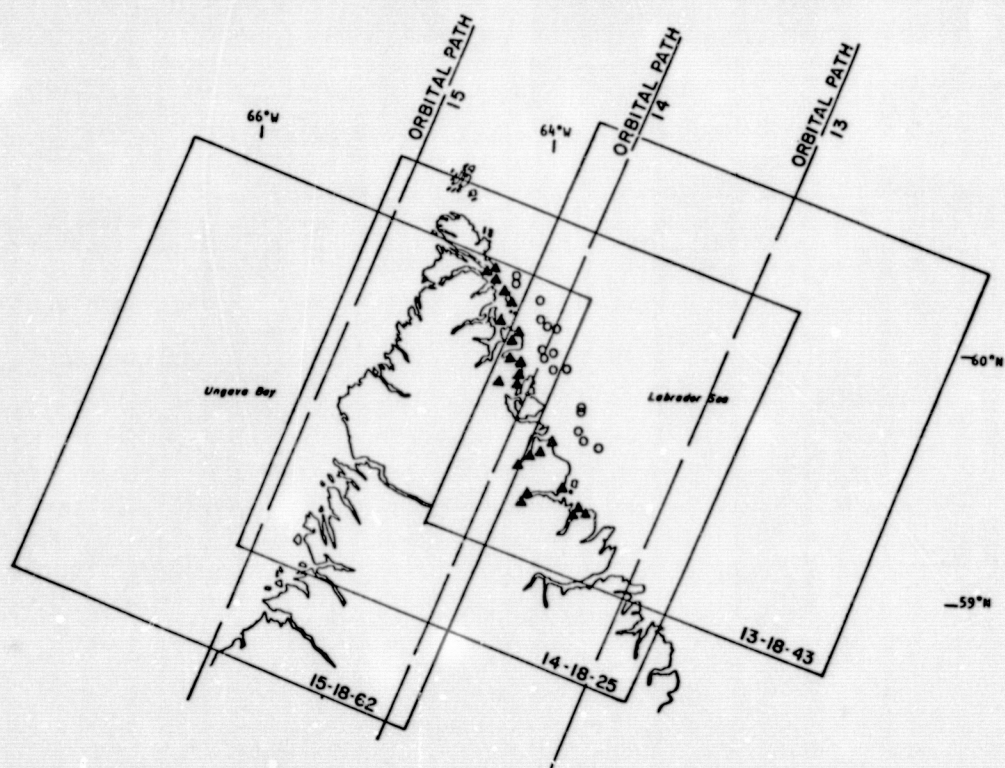


FIGURE 1 - LANDSAT COVERAGE

LANDSAT coverage of the survey area showing the overlap of the images. The land area tended to be cloud-covered, forcing the selection of control points to the narrow coastal band as shown.

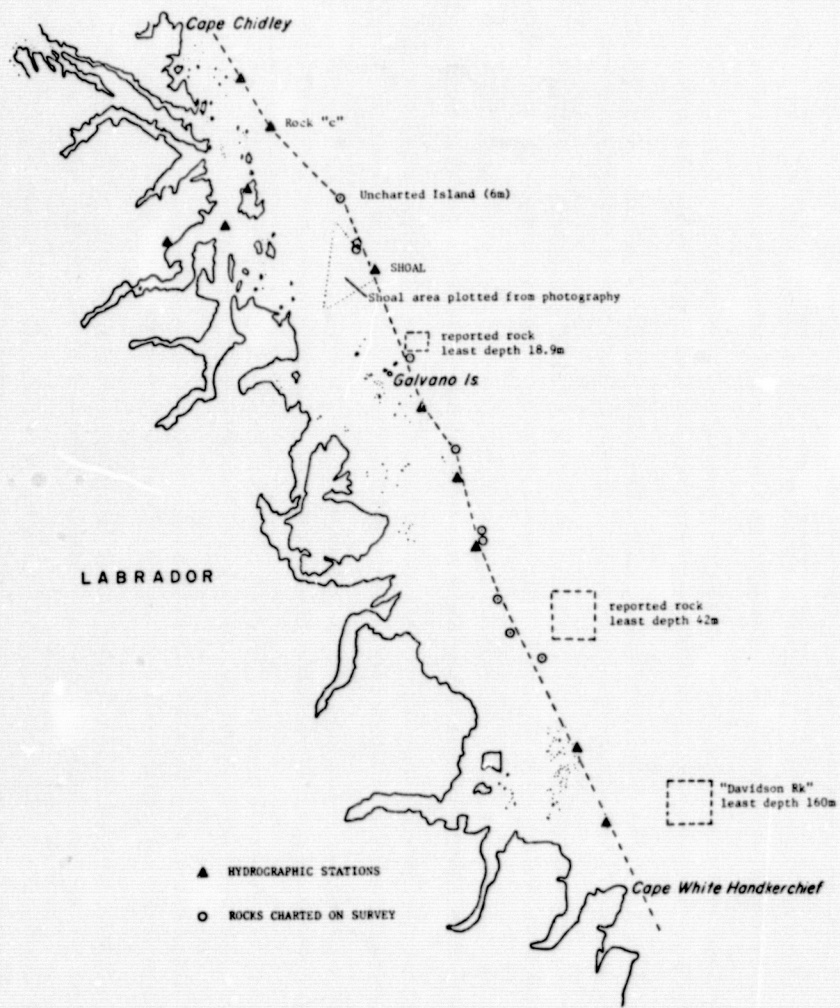


FIGURE 2 - BAFFIN SURVEY ROUTE

CSS BAFFIN survey of the coast of Labrador from 59°15'N to 60°25'N during 1976 to chart offshore features and check reported rocks.

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N78-14525

ALTERATION MAPPING AT GOLDFIELD, NEVADA, BY CLUSTER
AND DISCRIMINANT ANALYSIS OF LANDSAT DIGITAL DATA

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ABSTRACT

The ability of Landsat multispectral digital data to differentiate among 62 combinations of rock and alteration types at the Goldfield mining district of Western Nevada was investigated by using statistical techniques of cluster and discriminant analysis. Multivariate discriminant analysis was not effective in classifying each of the 62 groups, with classification results essentially the same whether data of four channels alone or combined with six ratios of channels were used. Bivariate plots of group means revealed a cluster of three groups including mill tailings, basalt and all other rock and alteration types. Automatic hierarchical clustering based on the fourth dimensional Mahalanobis distance between group means of 30 groups having five or more samples was performed using Johnson's HICLUS program. The results of the cluster analysis revealed hierarchies of mill tailings vs. natural materials, basalt vs. non-basalt, highly reflectant rocks vs. other rocks and exclusively unaltered rocks vs. predominantly altered rocks. The hierarchies were used to determine the order in which sets of multiple discriminant analyses were to be performed and the resulting discriminant functions were used to produce a map of geology and alteration which has an overall accuracy of 70 percent for discriminating exclusively altered rocks from predominantly altered rocks.

1. INTRODUCTION

One of the most difficult problems involved in extracting geologic information from Landsat multispectral data is deciding which spectral band or combinations of bands should be used. Preliminary interpretation of individual bands or ratioed images (Rowan and other, 1974) is satisfactory for discriminating among geologic materials whose spectra permit them to be easily distinguished from each other, but the method is affected by image processing and interpreter bias. A more objective method involves statistical analysis of digital data obtained from a test site which has been mapped by traditional field methods.

2. GEOLOGY

The Goldfield mining district of Nevada provides an excellent site to test the value of Landsat data for mineral exploration in an arid region. The surface geology and alteration of the district have been mapped in great detail in conjunction with geochemical surveys conducted by the U.S. Geological Survey (Ashley and Keith, 1973). The study area is underlain by approximately 40 km² of hydrothermally altered Tertiary volcanic rocks which contain zones of silicified outcrops associated with the gold ore. The altered area was sampled using a 152-metre (500-foot) grid and the rock and alteration type was noted at each of 1954 sample sites (Ashley and Keith, 1973).

3. DATA EXTRACTION

Landsat pixels (picture elements) which were entirely within a single geologic unit were selected by overlaying a plot of the pixel outlines on a 1:24,000-scale geologic map. The resulting 786 geologically homogeneous pixels were arranged in 62 groups containing a variety of lithologies and alteration types. These included montmorillonite, illite-kaolinite and

silicic alteration types, as well as colluvial soils (Table I). The original Landsat data were converted to reflectance units for each channel by using light and dark areas which have had their reflectances determined in the field. Uneven lighting caused by shaded and sunlit slopes was minimized by using high-sun elevation (61 degrees) Landsat data acquired on June 30, 1973 (scene number 1342-18003). The data were corrected for noise lines by using the means and standard deviations of each of the six sets of scan lines and the grand mean and standard deviation of the test area to "destripe" the data of each channel.

4. DISCRIMINANT ANALYSIS

Stepwise multivariate discriminant analysis in the form of the BMD07M computer program (Dixon, 1973) was used to determine the ability of Landsat multispectral data to discriminate among the many rock and alteration types present at Goldfield. Classification results based upon 61 groups (mill tailings were not included in the analysis) and the data of four channels, six ratios and a combination of channels and their ratios were used in the analysis but the results were discouraging. Although the basalt group was correctly classified 23 of 24 times, the other groups could not be classified on the basis of their Landsat spectra with any degree of confidence.

5. SCATTER DIAGRAMS

In an attempt to determine spectral subgroups which might be useful for classification purposes, graphical clustering was performed by plotting pairs of channels against each other for all six combinations of channel pairs. The channel means of each of the 62 groups were plotted and the resulting scattergram patterns interpreted (Figures 1a through f). Three major clusters are present in each of the six plots and include mill tailings, basalt and all remaining materials. Ellipses enclosing 90 percent of the data were constructed from the statistics for each of the three major clusters. Only a few very dark or very bright groups have means which plot outside the boundaries of the 90 percent ellipse for the samples of the central cluster. Although altered rocks were generally more reflectant than fresh rocks, altered and unaltered rocks do not form distinct clusters.

6. HIERARCHICAL CLUSTERING

Automated hierarchical clustering was performed using 30 groups, each of which contained five or more pixels. The computer program used was the HICLUS program (Johnson, 1967) which requires a matrix of similarities or dissimilarities. The fourth-dimensional distances from each group to all the other 29 groups was first considered as a measure of dissimilarity, but the wide range of variances and correlations between variables for each group would not have been taken into account. For this reason, the fourth-dimensional Mahalanobis distance (M-distance) from each group to each of the other 29 groups was used as a matrix of dissimilarity.

7. DENDROGRAMS

The results of the HICLUS program were plotted in the form of a dendrogram for both the "connectedness" and "diameter" methods which the program uses for clustering. The "diameter" method gave the most geologically meaningful results and confirmed clusters observed in the pair-wise plots of channel values. The three groups which formed the most distinct clusters were mill tailings, basalt flows and a pair of groups consisting of a rhyolite flow and kaolinite-bearing quartz monzonite. The remaining groups were divided into unaltered and predominantly-altered clusters, with the predominantly-altered cluster further subdivided into an andesite-dacite branch and a latite-and-others branch (Figure 2).

8. SEQUENTIAL CLASSIFICATION

The dendrogram obtained by hierarchical clustering was used to construct a "decision tree" to determine the order in which pair-wise discriminant analyses should be made for the four-channel data. The following sequential classification results were obtained by using the BMD07M program (Dixon, 1973) to decide the first four discriminant analysis decisions required to classify the training data. Prior probabilities were assumed to be 0.50 for each pair of groups.

- | | |
|--|--|
| 1. Mill Tailings (11/11=100.0%)..... | Natural materials (774/775=99.9%) |
| 2. Basalt flows (23/24=95.8%)..... | Non-basaltic rock (716/751=95.3%) |
| 3. Rhyolite and
quartz monzonite (12/15=80.0%)..... | Darker rocks (622/736=89.9%) |
| 4. Exclusively unaltered
rocks (84/114=73.7%)..... | Predominantly
altered rocks (457/622=73.5%) |

If the third pair of groups is eliminated by assuming that the two highly reflectant units constitute less than two percent of the study area, then the product of success rates for group pairs 1, 2 and 4 is equal to 70 percent for altered versus unaltered rocks. Results based on four channels and six ratios were also used as a basis for discriminant analyses, but the classification results were the same as, or only a fraction of a percent better than, those obtained by using the four-channel data alone. Essentially the same classification scores resulted when alternate samples were used to derive training and test groups.

9. AUTOMATIC GEOLOGIC MAPPING

The discriminant functions generated by using the three group pairs described above were used to produce a geologic map depicting altered areas by modifying the STANSORT computer program (Honey, Prelat and Lyon, 1974). The resulting pattern of alteration, although "grainy" in appearance, closely resembles the pattern of argillic alteration determined by field mapping (Figures 3a, b and 4a). The appearance of one of the images was improved (Figure 4b) by using the same discriminant functions to classify data smoothed by a weighted 3 x 3 pixel matrix (Maxwell, 1976). Although some of the very small areas of mill tailings and basalt are eliminated by using smoothed data, the resulting image depicts patterns of argillic alteration which closely resemble those mapped by traditional field methods.

10. ACKNOWLEDGEMENTS

I would like to acknowledge the assistance of Prof. R. J. P. Lyon of the Stanford Remote Sensing Laboratory, Prof. Paul Switzer of the Stanford Statistics Department, Dr. Roger Ashley of the U.S. Geological Survey, and the staff of Stanford's Institute for Mathematical Studies in the Social Sciences. I am also grateful to H.E.W. for providing a fellowship (G00-75-03882) for thesis work in mineral exploration. Computer funds were provided by a number of sources and include the following: NASA contract NSG-5050, U.S. Geological Survey, Minerals Exploration (Union Oil), Kerr-McGee Corp., Phillips Petroleum, and most recently, the Government of Libya.

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TABLE I EXPLANATION OF SYMBOLS USED FOR ALTERATION¹ AND GEOLOGY²

ALTERATION TYPES:

- u Unaltered rock, includes propylitized (p) and diagenetically or deuterically altered rocks (d).
- c Colluvial soil.
- m Montmorillonite-bearing argillized rocks.
- k Illite-kaolinite-bearing argillized rocks.
- s Silicified rocks.
- x Alteration type unknown, xTb is probably unaltered.

GEOLOGIC UNITS:

- Qmt Mill tailings
- Q ALLUVIUM AND COLLUVIUM (Quaternary) Sand and gravel, locally bearing cobbles and boulders.
- Tb BASALT Includes Malpais Basalt (Miocene or Pliocene), Basalt of Blackcap Mountain (Miocene) and Mira Basalt (middle Miocene).
- Ts SIEBERT TUFF (Miocene) Includes andesite breccia of Ransome (1909). Volcanic conglomerate and sandstone; tuffaceous conglomerate, sandstone and shale.
- Tsp Silicic vitric air fall, commonly with pumice lapilli.
- Te ESPINA BRECCIA (lower Miocene) Rhyolite tuff breccia locally with lapilli tuff interbeds.
- Tct TUFF OF CHISPA HILLS (lower Miocene) Dacite vitrophyre of Ransome (1909). Rhyodacite-quartz latite ash-flow tuff.
- Tadt ANDESITE MEGABRECCIA (lower Miocene) Jumbled blocks from units Tma, Td and Tdtb. Probably represents landslide deposits.
- Td PORPHYRITIC RHYODACITE (lower Miocene) Dacite of Ransome (1909). Several rhyodacite flows containing plagioclase phenocrysts and varying proportions of hornblende, biotite and hypersthene phenocrysts.
- Tdtb Rhyodacite tuff breccia.
- Tdwt Rhyodacite welded tuff.
- Tma MOUNTAIN ANDESITE (lower Miocene) Flows and tuffs, including pyroxene-hornblende and pyroxene trachyandesite, pyroxene-hornblende and hornblende-biotite rhyodacite and minor quartz latite and basalt.
- Tsr SANDSTORM FORMATION (Oligocene) Sandstorm rhyolite of Ransome (1909). Fluidal rhyolite bearing small sanidine and quartz phenocrysts.
- Tswt Silicic tuff, lapilli tuff and tuff breccia characterized by abundant lithic fragments.
- Tssh Tuffaceous shale.
- Tl QUARTZ LATITE (Oligocene) Latite and Kendall Tuff of Ransome (1909). Fluidal porphyritic quartz latite with plagioclase, biotite and hornblende phenocrysts.
- Tlag Quartz latite "agglutinate"
- Tvr VINDICATOR RHYOLITE (Oligocene) Fluidal rhyolite and rhyolite flow breccia bearing quartz phenocrysts.
- Jqm QUARTZ MONZONITE (Jurassic) Alaskite of Ransome (1909). Leuco-quartz monzonite and quartz monzonite, mostly medium-grained, with a few aplite dikes and mafic inclusions.
- Op PALMETTO FORMATION (Ordovician) Siliceous shale, siliceous argillite and minor limestone.

¹ Ashley, R. P. and Keith, W. J., 1973, Geochemistry of the altered area at Goldfield, Nevada, ..., U.S. Geol. Survey Open-file rept.

² Ashley, R. P., 1975, Preliminary geologic map of the Goldfield mining district, Nevada: U.S. Geol. Survey Map MF-681.

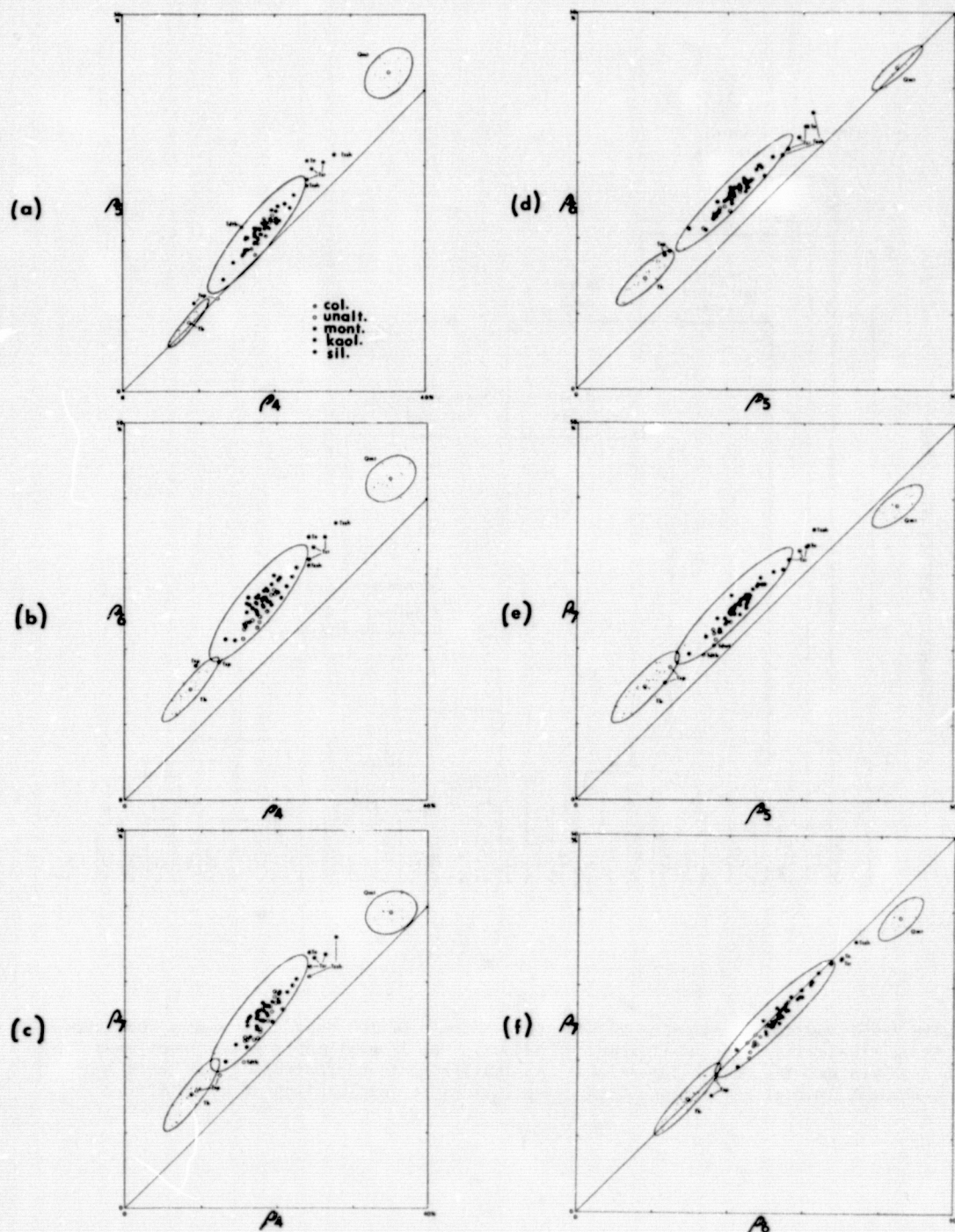


Figure 1--Plots of Landsat spectral bands after conversion of brightness units to apparent reflectance by using ground calibration sites. Ellipses enclose 90 percent of the data in each of the three major clusters, with symbols for group means representing colluvial soil, unaltered outcrop, montmorillonite-bearing, illite-kaolinite-bearing and silicified rocks. Data extracted from Landsat scene 1342-18003, June 30, 1973.

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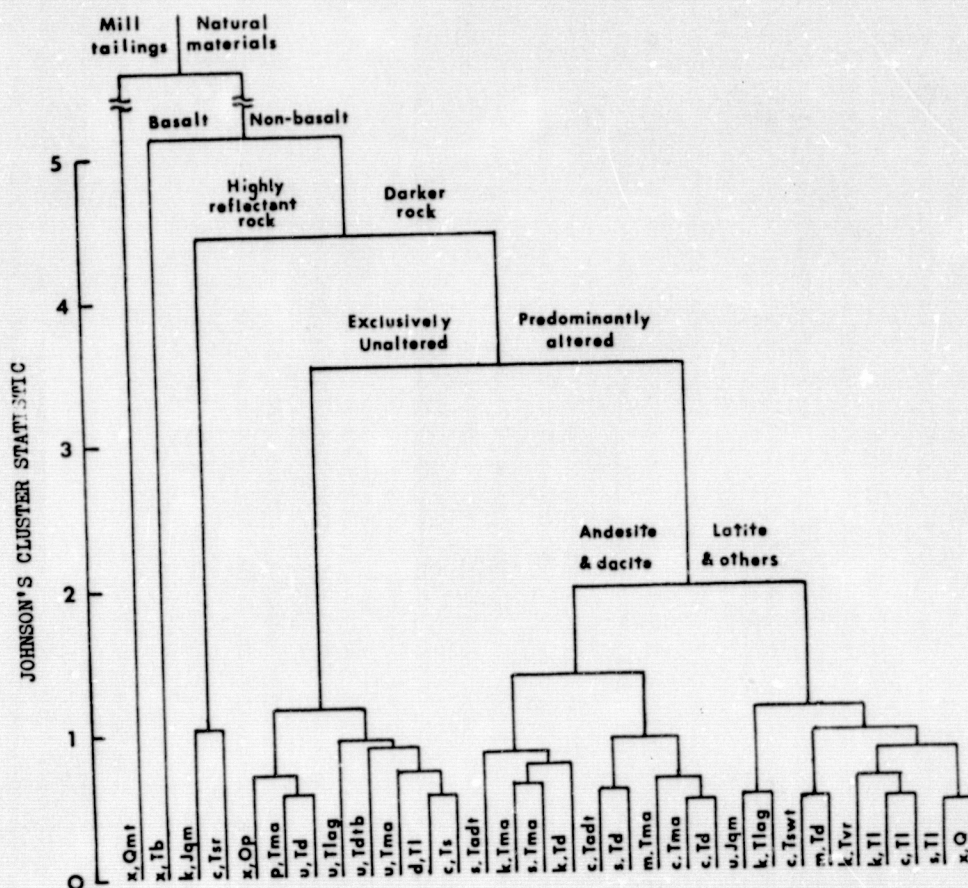


Figure 2--Dendrogram illustrating results of Johnson's HICLUS computer program for hierarchical clustering using the "diameter" method. The dissimilarity measurement used for the analysis was the fourth-dimensional Mahalanobis distances between group means based on 4-channel Landsat reflectance data. See Table I for explanation of symbols.

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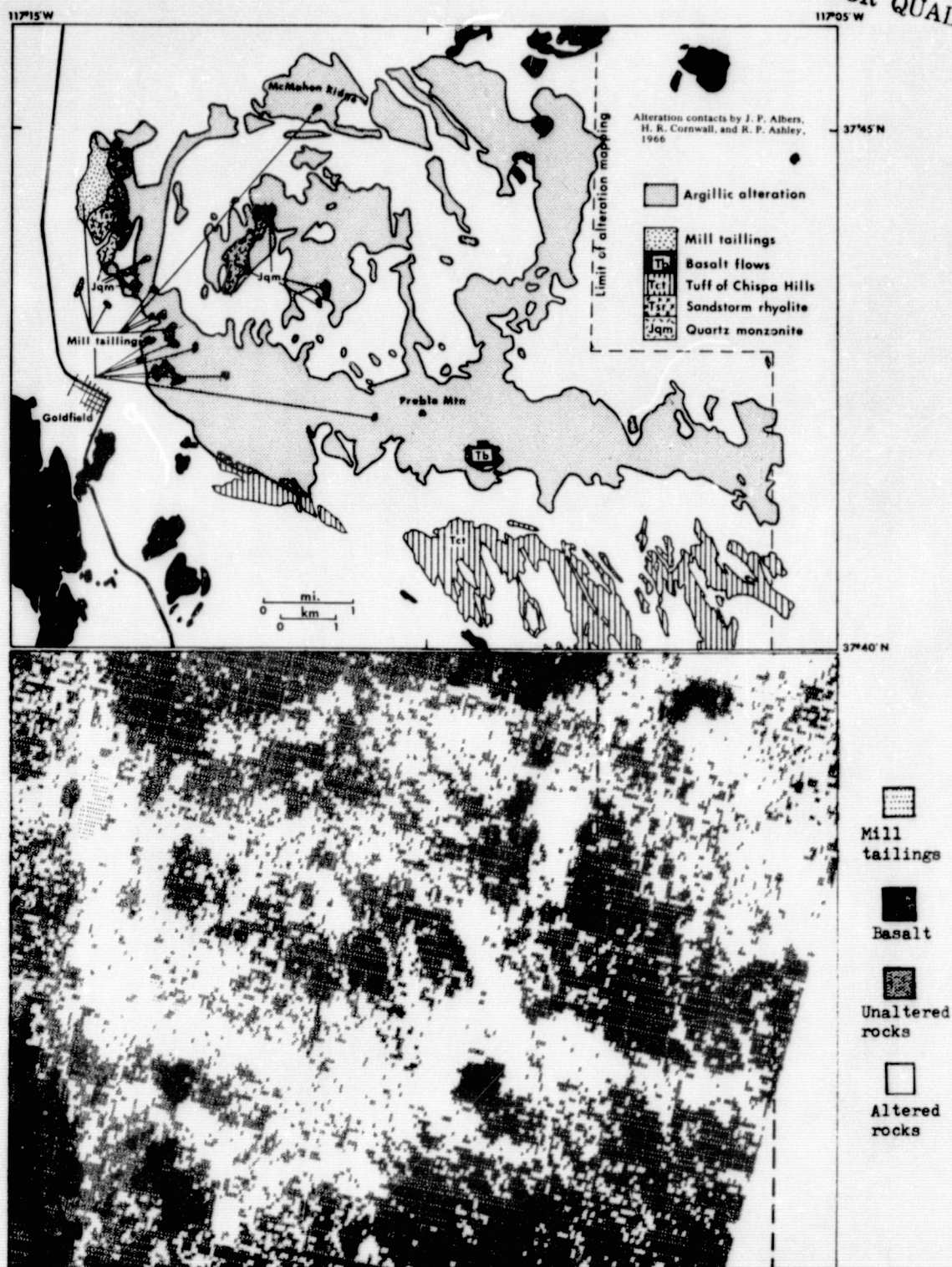


Figure 3--Comparison of geology and alteration at Goldfield as mapped by traditional methods (a) and by hierarchical discriminant analysis (b).

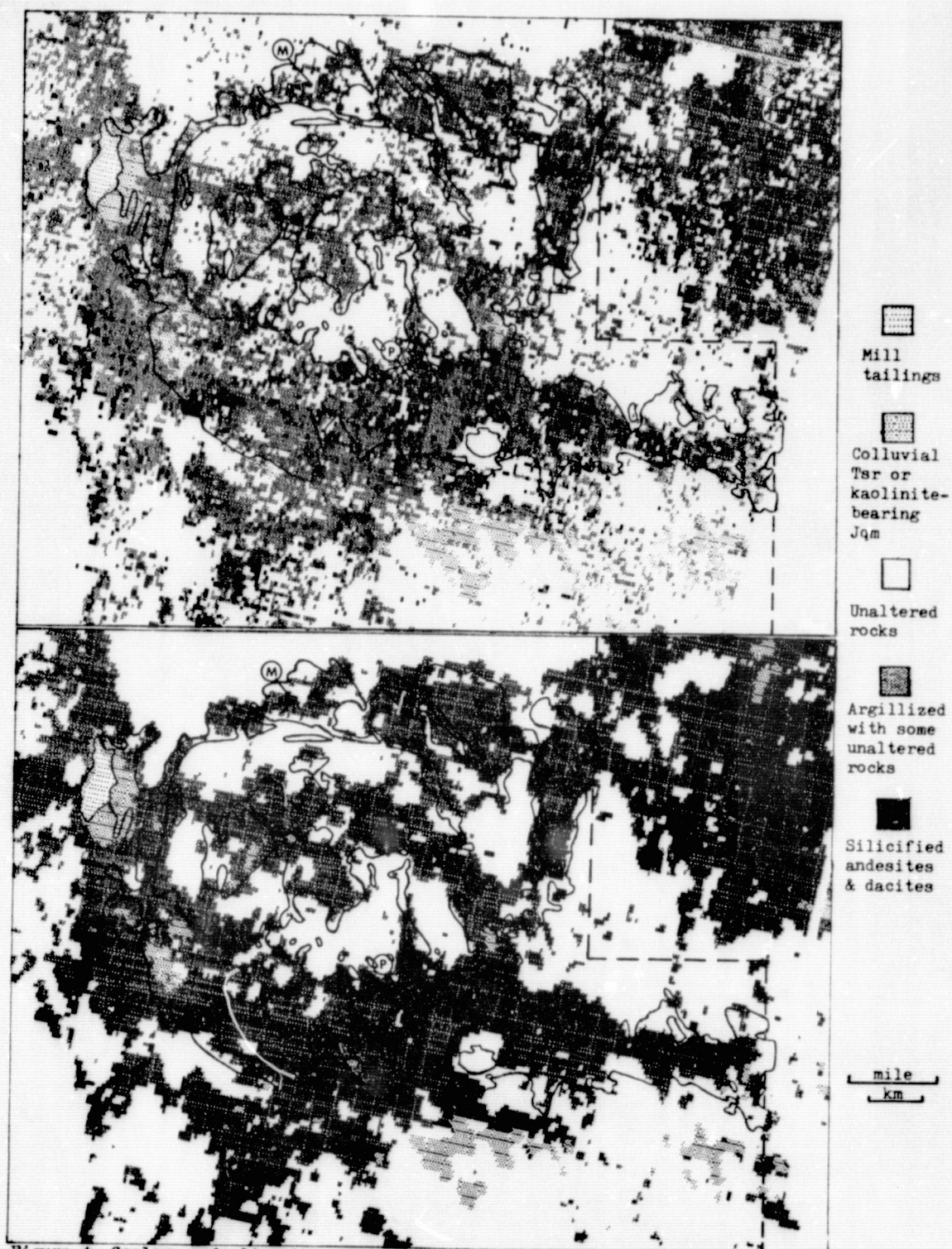


Figure 4--Geology and alteration at Goldfield based on single pixels (a) and a 3x3 matrix of pixels (b). Both MacMahon Ridge (M) and Preble Mtn. (P) contain areas of silicic alteration.

962
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QUATERNARY GEOLOGIC MAP OF MINNESOTA

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The new Quaternary Geologic Map of Minnesota is a compilation based both on the unique characteristics of satellite imagery and on the results of previous field investigations, both published and unpublished. The use of satellite imagery has made possible the timely and economical construction of this map to serve Minnesota for the many years it will require to complete a systematic, detailed field investigation.

In Minnesota the Quaternary geology is essentially Pleistocene geology, which in turn is dominated by repeated glaciation. It is the geology of materials and conditions at or near the surface and influences most aspects of land use, resource development and environment. The most recent investigation to encompass the entire State was published as installments from 1915 to 1919 and is now outdated by subsequent investigations in specific areas and improvements in technology. A new map covering the entire State was needed.

The scale chosen for the map was 1:500,000 to allow the presentation of the information on one sheet with enough detail to be specific. Minnesota covers an area of 84,000 square miles. Previous geologic investigations varied considerably in area and scale, quality, purpose and number in different parts of the State. The map needed is one that reflects a uniform interpretation of the geology with continuity across the State.

A systematic and detailed field investigation was among the several methods that were considered for preparing a new map. However this would have required many man-years and hundreds of thousands of dollars, and it was hoped that an updated version of the map would be available while field work was in progress.

A synthesis of the available reports of investigations into a single compilation presents problems in resolving conflicts between reports and in interpreting areas for which information is lacking. Nonetheless, getting this information together at the same scale and with the same description was an important first step for preparing the map.

The topographic maps produced by the U.S. Geological Survey were a possible source of base information to expand upon the evidence provided by geologic investigators since topography is useful for interpreting glacial geology. However, these maps contain no clue as to the composition of the surficial materials, the large scale would make reduction to the desired scale a cumbersome process, and regional relationships are difficult to evaluate--there are about 1480 topographic sheets for the State, and some areas still lack coverage.

Interpretation of aerial photographs was another possibility considered for updating the Quaternary geologic map. There are about 20,000 aerial photos in stereo pairs taken over the past 40 years that would be needed to give coverage of the State. Difficulties included cost, variability in quality of the photography, and the fact that each photo shows such a small area. The limited scene emphasizes details too small to represent on the final map and obscures an understanding of regional relationships.

The use of LANDSAT imagery offered many advantages. Each LANDSAT image covers a broad area. Multi-seasonal coverage for the entire State was available.

The imagery had excellent control for registry to the base map. The subject resolution was consistent with the detail needed to identify features at the 1:500,000 scale. On the other hand, there was no assurance that glacial features could be identified with any certainty; an earlier report on use of LANDSAT imagery to identify till in the Minneapolis-St. Paul metropolitan area was not entirely favorable, and glacial features on the imagery are not striking. It was apparent that the LANDSAT imagery alone, without ground truth for verification of what was visible on the imagery would not suffice.

In order to bring the reports of field investigations to bear on LANDSAT imagery interpretation, the following four-step procedure was followed:

1. The literature, together with the records of several agencies, was reviewed and assembled. A preliminary bibliography of the materials on Quaternary geology that are readily accessible to the public was assembled.

2. The 157 published and manuscript maps based on field studies of Quaternary geology in all or parts of the State were transferred to the scale of 1:500,000 and a single rendition at this scale was compiled.

3. The rendition from field studies was compared with satellite imagery to reconcile discrepancies and establish the areal continuity of the various units, and a preliminary map of the Quaternary geology was prepared. This phase is discussed in detail below.

4. The preliminary Quaternary Geologic Map of Minnesota has been submitted for review to over thirty people who have been active in studies of the Quaternary geology of the State; suggestions and comments which will make the map more accurate and useful are now being received.

It was decided that the imagery would be interpreted visually. Contrast stretching to emphasize the subtle differences between units, in conjunction with computer compatible tapes of the selected scenes, was considered for identifying till terrains. However there are a number of severe limitations to the use of digital processing on a large region. Some 60 training sets for the various mapping units would have been necessary. The areal extent of the study entailed the use of images taken at different dates with varying quality and ground conditions. Since variation within a single image can often affect the accuracy of training sets, the need to carry these sets to other images representing a different time and condition suggested that some complications would have been insurmountable. Multi-seasonal registry of the scenes was essentially beyond the state of the art. Furthermore, spectral response is not necessarily the most dependable interpretive device, because the features are often recognizable by their shape and location relative to each other and by textural characteristics for which it is hard to establish training sets.

The LANDSAT imagery for the Quaternary geologic map was selected first for cloud-free coverage. Imagery for early spring leaf-off, late summer full foliage under minor stress, and winter snow cover was obtained at the scale of 1:1,000,000 in the form of standard transparent false-color composites of spring and summer scenes and transparent, black and white, band 7, winter scenes. A black and white paper print of the band 7 early spring scenes at a scale of 1:500,000 was used as a base map for locating features at the scale of the final map. About 20 scenes were needed for complete coverage of the State.

A mylar overlay registered to the early spring 1:1,000,000 false color transparency was used to record the interpretations. This overlay was then transferred to the summer and winter scenes, also at 1:1,000,000 to confirm interpretations and add new information. Finally the information was transferred to a sheet of three mil mylar overlying the band 7, 1:500,000 scale print, a base map showing lakes and rivers, and the map compiled from field studies. The map sent out for review was then generated.

All of the imagery was useful, especially the early spring false color composite transparencies taken after the snow was gone, before refoilation

and on crisp, clear days. These had the greatest tonal variation for identification of till types. Late summer coverage revealed areas where the vegetation was under some stress, mostly in areas of greater relief and coarser till textures. The low sun angle and contrasting shadows on the snow in the winter scenes helped to identify low topographic features in the unforested areas. These scenes were also helpful in distinguishing prairies, fields, deciduous and coniferous forests, and open bogs because the snow covered the low vegetation and reflected through the bare deciduous trees. Because the images were taken at the same time of day, valleys and ridges oriented northeast-southwest were more conspicuous than others.

During the interpretation, distinctions noted on the LANDSAT imagery were recorded for areas identified as specific mapping units. The following paragraphs summarize the unique combinations which led to recognizing the features elsewhere on the imagery.

The various till units reflected their respective topography, texture and inherent fertility. The rich, clayey Des Moines tills were very dark in the spring, dark red in the summer, and relatively smooth white in the winter; they generally support the most agriculture. The Wadena till was generally buff or brown mottled with greys on the spring coverage, mottled with reds and dark reds on the summer coverage, and with dark and medium greys displaying deciduous forests and limited agriculture on the winter scenes. The Superior tills in the spring were generally dusky rose, pink and lavender; summer images were red and bright red flecked with mottles of pink, yellow and white with low areas in dark blue or lavender; winter scenes were grey and dark grey, indicating mixed deciduous and coniferous forests, and scattered agriculture. The spring scenes of the Rainy tills were often brown or dusky with yellow flecks, and where foliage had appeared they were often bright smooth reds. In the summer scenes they were reds and bright reds with shades of blue on the wetlands; in the winter scenes they were smooth dark gray and grey colors indicating coniferous forests and little agriculture.

The following image characteristics reflect depositional environments of glacial materials comprised by the various till units as indicated by colors and seasonal variations.

End moraines were usually forested with little agriculture. In the spring they were usually light pink or dusky with highlights of red. In the summer they were usually smooth red and dark red, often with flecks of white and yellow. In the winter they were shades of smooth dark grey where forested and elsewhere showed a rough topography.

Stagnation moraines generally contained many lakes and in appearance were something between that of ground moraine and end moraine. The spring coverage often contained bright red areas of ice contact features. In the summer the areas were mottled red, pink and blue. In the winter they were mottled grey and white. Agricultural use varied.

Ground moraines were mottled blues, roses or pinks in the spring scenes. Often they were red flecked with white or yellow in summer. They appeared as smooth white or grey in the winter. Their use for agriculture and forestry varied widely across the State.

The appearance of lacustrine sediments on the imagery varied widely. The Glacial Lake Agassiz clays were black in the spring, red in the summer and a uniform white in the winter coverage, revealing intensive agriculture. The Lake Agassiz basin is a truly outstanding feature on the images. The other lake clay sediments had a mottled appearance because of bogs and wetlands; they were usually mottled blue, lavender and pink in spring, red and dark red in summer, and grey and light grey in winter scenes, with little agriculture. The lake sands and gravels of Glacial Lake Agassiz and some other lakes are often abandoned beaches and bars. In the spring the false color composites show them as white, yellow or pink, in summer as pink or white; in the winter the unforested beach ridges were readily identifiable. Other lacustrine sands are often mottled and spotted pink and yellow with blue and dark blue in the spring, red and dark red in the summer and shades of grey in the winter coverage,

revealing limited agriculture. In general the lacustrine sediments were recognizable, despite considerable variability in appearance.

Alluvium was usually distinguishable because it occurs along the streams, although it is difficult to identify it in the forested areas. Depending on the vegetation it appeared in spring as light red or dark blue, in summer usually as very red, and in winter as a flat smooth white or dark grey.

Terraces were not always specifically definable. Where they were recognizable they were a smooth even color in all seasons. They occur near streams and alluvium.

Peat areas reflected their wet nature. They were usually dark blue, black or brown with spots of pink and red in the spring. In the summer they were red and dark red mottled with purple and blue. In the winter they were mottled white, grey and black. The pattern of colors also helped to identify them. They have virtually no agriculture.

Colluvium was identified by its forests, dendritic pattern and dissected appearance in all seasons. It was usually light red in spring, dark red in summer and black in winter.

Two types of loess were recognized. One unit was less than five feet thick and one was over five feet deep. The thin loess was a medium rose compared to pink for the deep loess in the spring. In late summer the thin loess was a rose or medium rose while the deep loess was dark rose in color. In the winter the thin loess was commonly smooth white or light grey, whereas the deep loess was more commonly visibly dissected by streams. Dune areas were usually too small to identify effectively.

The distinctive pattern of drumlin fields could usually be seen on images for all seasons. Abandoned beaches were identifiable, but strand lines were too small to determine at all. Meltwater channels and glacial lake outlets were apparent, particularly on winter photographs of unforested areas. Glacial ridges or ripple till could be recognized, especially in the spring coverage. The solitary and sinuous forms of eskers blended in with the general topography of till deposits; better resolution would have been helpful. Kames were difficult to identify. They were best seen in early spring coverage where they appeared as a bright red, but their existence must be confirmed on the ground.

LANDSAT imagery interpretation proved more useful than expected. Most of the geologic units could be identified by extrapolating from specific sites where the geology had been investigated into areas where little was known. The excellent geographic registry coupled with the multi-spectral record of these images served to identify places where the geologic materials responded to their ecological environment and where the ecology responded to the geologic materials. Units were well located on the map at the scale selected for the study. Contacts between till units could be placed with reasonable accuracy. The reference points that were used to project delineations between units (rivers, lakes, hills, roads and other features), which had not been accurately located on early maps, could be accurately located with the help of the imagery. The tonal and color contrasts, the patterns reflecting geologic change and the resolution of the images permitted focusing attention on features which could be represented at the final scale of the map without distraction by other interesting but site-specific details.

REMOTE SENSING-AIDED SYSTEMS FOR SNOW QUANTIFICATION,
EVAPOTRANSPIRATION ESTIMATION, AND THEIR APPLICATION
IN HYDROLOGIC MODELS

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ABSTRACT

The objective of this paper is to reflect the design of general remote sensing-aided methodologies to provide the estimates of several important inputs to water yield forecast models. These input parameters are snow areal extent, snow water content, and evapotranspiration. The study area is Feather River Watershed (780,000 hectares), Northern California.

The general approach involves a stepwise sequence of identification of the required information, sample design, measurement/estimation, and evaluation of results. All the relevant and available information types needed in the estimation process are being defined. These include Landsat, meteorological satellite, and aircraft imagery, topographic and geologic data, ground truth data, and climatic data from ground stations. A cost-effective multistage sampling approach is being employed in quantification of all the required parameters. The physical and statistical models for both snow quantification and evapotranspiration estimation are developed. These models utilize the information obtained by aerial and ground data through appropriate statistical sampling design.

In case of snow areal extent, the procedure developed has been applied to three dates in April 1973 with satisfactory and cost-effective results. The results are maps of snow areal extent along with their variance, population ratio estimator, confidence intervals, and allowable error for each date.

In case of snow water content, the Landsat-aided system has yielded relatively precise and cost-effective watershed-wide estimates for spring of 1973. The results to date indicate a correlation coefficient of 0.8-0.85 between remote sensing-aided snow water content index data on a sample unit basis and corresponding ground snow water content measurements collected by California Department of Water Resources.

In case of evapotranspiration (ET), the areal distribution of the input climatic data (i.e., temperature, solar radiation, etc.) for ET models is being prepared. The vegetation-terrain analysis has been completed and the areal distribution of elevation, slope, and aspect is produced. The level I ET models have been applied to Spanish Creek Watershed (a sub-basin of Feather River Watershed). The results are in general agreement with the values of evapotranspiration, based on conventional methods, reported in the literature for similar area.

INTRODUCTION

The development of the water resources is an example of the application of human knowledge and experience to the management of an environment. Biswas (1970) traces the history of hydrology to about 3200 B.C. The early inhabitants of the American Southwest had built well-developed water resources utilization systems (Garstka, 1972).

We are fortunate to be living in the present era. The dams are new and reservoirs are not filled with the sediment. The geologists tell us that a lake is an evanescent feature; that all lakes, both large and small, will sooner or later, through the action of never-ceasing forces of nature, become filled with sediment. The management of watersheds producing the inflows to the reservoirs becomes therefore an extremely important function since it has been demonstrated that watershed management practices can exert a major influence upon the sediment yield of streams.

Practically all of the water available and suitable for massive carry-over storage impound-

ments of the new era is yielded by the wildlands: the grasslands and forests. Water yield management of the water-yielding areas is fundamental to the whole structure of society (Garstka, 1972). The old world recognized the importance of watershed management very long ago. There are areas in Switzerland which have been under forest management for several centuries. For example, the Canton of Valais has had a strict conservation policy which has prohibited all cutting of existing forests in specific areas.

As the population increases there is an inevitable increase in the value of water and in the price people will be willing to pay to secure water. The concentrations of population such as the Los Angeles Metropolitan area and San Francisco Bay area, for example, are assured of domestic and municipal water because of the existence of massive carry-over storages at hundreds of miles away from the point of water demand.

As it is indicated by many investigators, our knowledge of the environment, especially with respect to climatology and hydrology of the water yielding areas, is inadequate. To date, precision of operation has been restricted to the hydraulics of conveyance and distribution systems. Relatively little hydrologic research has been conducted in the water resource-producing drainage basins in the wildland areas. Watershed analysis, in particular, plays an important role in water resources management.

The fundamental physical data upon which water resources developments are based consist essentially of hydrologic, meteorologic, climatologic, geologic, ecologic, biologic, and pedologic observations. Collection of this data bank requires a great expenditure of time and effort in the water yielding drainage basins and in the project development areas. Timely, spatial, and frequent observations obtained by remote sensing technique provides a fundamental physical data bank for watershed characterization and better water resources management. This remote sensing-aided data bank include the useful information both in water quantity and water quality.

The major input parameters to most of the water yield forecast models include precipitation, snow water equivalent, and water loss from the watershed. Better estimates of these parameters results a better water yield forecast and consequently better water resources management. Available data from Landsat and Environmental satellites combined with high-and-low-altitude aircraft data and ground observations in a multistage sampling frame makes it possible to collect adequate required physical and climatic data over the large basin(s) of interest for better water yield prediction.

Objective:

The objective of this investigation, funded by a NASA Grant NGL 05-003-404, is to design a general remote sensing-aided information system to provide time-and-location-specific estimates of several important inputs to water yield forecast models. These input parameters include snow areal extent, snow water content, and water loss to the atmosphere (evapotranspiration). The technique, under development in this study are being tested on the water source basin for the California Water Project. This area is known as the Feather River Watershed, FRW, (780,000 hectares). The methodology for estimating evapotranspiration (ET) is being applied to the Spanish Creek Watershed, SCW, (47,500 hectares), a sub-basin of the Feather River Watershed.

MATERIALS AND METHODS

In this section the procedure for estimating areal extent of snowcover is discussed at the beginning. The results of snow areal extent will then be used in a technique developed for snow water content estimation. The last part of this section will cover the methodology developed for evapotranspiration estimation.

Methodology for Estimating Areal Extent of Snowcover:

From the late forties to date, many studies have included use of aerial photography to measure the areal extent of snowcover (Parsons and Castle, 1959; Finnegan, 1962; Leaf, 1969). However, it was not until the early 1960's that one could attain a synoptic view of large geographical areas through earth orbiting satellites. Today, a wide variety of satellites are collecting massive amount of data that could be utilized to map the snow areal extent in a

repetitive mode over the large watersheds. Imagery obtained from Landsat-1 has provided the raw data for this study. The method used to estimate areal extent of snow at the Remote Sensing Research Program (RSRP) is based upon the analysis of imagery defined by artificial units (grids) with environmental considerations (Katibah, 1975). This procedure allows the image analyst to make decisions in discrete units of the imagery as to the areal extent of snow based upon factors effecting the snowpack.

Three cloud free dates in spring 1973, April 4th, May 10th, and May 28th, covering the Feather River Watershed were used for this snowcover inventory. Landsat imagery in the form of simulated color infrared enhancements of band 4, 5, and 7 was utilized for the interpretation procedures (Katibah, 1973). On these three dates random transects were flown across the watershed using a 35 mm camera to acquire large scale photography required as an aid in determining the actual snow condition on the ground.

To estimate the areal extent of snow, the Landsat-1 images were gridded with image sample units (ISU's), each equalling approximately 400 hectares. These image sample units were then transferred to the large scale photography where applicable. The image sample units on the areal photography were divided into five classes containing from 0 to 100% snowcover.

The gridded Landsat color enhanced images were then interpreted, sample unit-by sample unit, and coded using the following method to account for vegetative cover and density and to some degree, aspect and elevation. Scale matched simulated color infrared enhancements of Landsat-1 imagery were produced for April 4th, 1973; May 10th, 1973; May 28th 1973 and also for August 31st, 1972 in reflection print form. The April and May dates represent the snowpack and were gridded, while the August 1972 date, representing a cloud free summer image, was not gridded. The purpose of the August date was to provide a clear aerial view of actual ground relationships of vegetation/terrain features. The August date was superimposed with each of the snow-pack dates using a mirror stereoscope. Using this technique image analyst could observe what conditions actually occurred on the ground in the image sample unit he was interpretation for snow-pack.

The large scale photography were used to calibrate the Landsat data where applicable. The sample unit-by-sample unit interpretation of the Landsat imagery, was then used to find the estimate for the areal extent of snowcover in the watershed. Summation of each of the individual snow cover classes were used to estimate the areal snowcover of each image sample unit on the ground. By addition of these totals the areal extent of snowcover for the entire area was estimated.

This estimation of the areal extent of snow was based only on the Landsat interpretation results. To correct this estimate, the image sample units where snow areal extent "ground truth" was obtained (from large scale aerial photography) were compared with the same image sample units on the Landsat imagery. The relationship between the snow areal extent values on the corresponding Landsat and "ground truth" sample units is the basis for the application of the ratio estimator statistical technique (Cochran, 1963). This technique not only provides a correction for the original interpretation estimate, but also allows for an estimate of the precision of this estimate through the application of confidence intervals. The 95% confidence intervals around the areal extent of snow estimates were then calculated.

Methodology for Snow Water Content Estimation:

The rate of which the snow cover deplets is an index which is inversely related to the snow water equivalent and snowmelt runoff (Rango and Salomonson, 1975, Khorram, et al., 1976). The procedure used in this study is designed to generate an estimate of watershed-wide snow water content and an associated statement of precision. This system employs a stratified double sampling technique based on Cochran, 1963 and Raj, 1968 and used both ground snow course and Landsat data. Its objective is to combine snow water content information for the whole watershed, as obtained inexpensively from Landsat data, with that gained from a much smaller and more expensive sample of ground-based measurements at snow courses. This method is described below:

Black-and-white Landsat imagery for April 4th, May 20th, and May 28th, 1973 covering the Feather River Watershed (7,800 Km²) was obtained and transformed into a simulated infrared

color composite. In the color combining process, an ISU grid was randomly placed over each image so as to cover the watershed of interest. ISU's in this study represented areas of about 400 hectares.

Estimates of snow areal extent by Landsat ISU for previous year(s) or current snow build-up dates were made. Each ISU was interpreted manually as to its average snow areal extent cover class according to a snow environment-specific technique (Khorram, et al., 1976). Estimates of snow areal extent by ISU for Landsat snow season date was then calculated.

This snow areal extent data was transformed to snow water content data. Snow water content index was estimated from the following first order, time-specific model:

$$X_i = \sum_{j=1}^J (M_{ij})(G_j) K_i$$

where X_i = estimated snow water content for image sample unit i ,

M_{ij} = snow cover midclass point based on photo interpretation; expressed on a scale of 0.00 to 1.00 for image sample unit i on the j th Landsat snow season date,

G_j = weight assigned (0.00-1.00) to a past M_{ij} according to the date of a current estimate,

K_i = the number of times out of J that sample unit i has greater than zero percent snow cover, and

J = total number of snow season dates considered.

To insure reasonably high correlation between X_i and corresponding ground snow water content values, there usually should be at least three snow season dates considered ($J \geq 3$). Normally, one or two dates of Landsat imagery would be required during the early snow accumulation season. Occasionally, J may be only two, such as when the first date consists of an April 1st snow water content map based on past year's Landsat data. In all cases the sample unit grids on all dates must be in common register with respect to a base date grid location (see Figure 1).

All the image sample units were stratified into Landsat snow water content index classes. The number of ground sample units (GSU's) by stratum or snow courses required to achieve the allowable error criteria for the basin snow water content estimate was then calculated. The number of required ground samples may be determined (Thomas and Sharp, 1975) for individual strata according to the snow survey direct cost budget for the watershed of interest and according to the following stratum specific statistics: relative stratum size, Landsat snow water content variability, Landsat to ground correlation, and Landsat to ground sample unit cost ratio. This study employed six snow water index strata, with water content index values ranging from less than 0.1 to over 8. Such stratification was used to control the coefficient of variation of the overall basin snow water content estimate.

The GSU's were allocated among snow water content strata with equal probability within strata in accordance with stratified random sampling requirements. The following table summarizes the number of image and ground sample units required in each of six snow water content strata, given a cost per ISU of 15¢ and a cost per GSU of \$150.

The final product was the watershed-wide estimate of snow water content according to a summation of strata-wide snow water content estimates generated from regression equations relating the Landsat snow water content index data in each stratum to the corresponding sample of ground snow water content measurements.

Methodology for Watershed-Wide Estimation of Evapotranspiration:

Evaporation may be defined as the transfer of water vapor from a non-vegetative surface on the earth into the atmosphere. Evapotranspiration is the combined evaporation from all surfaces and the transpiration of plants. Except for the omission of a negligible amount of water used in the metabolic activities, evapotranspiration is the same as the "consumptive use" of the

plants. The fact that the rate of evapotranspiration from a partially wet surface is greatly affected by the nature of the ground leads to the concept of potential evapotranspiration. Penman (1948) defines potential evapotranspiration as "the amount of water transpired in unit time by a short green crop, completely shading the ground, of uniform height and never short in water."

A multistage, multiphase sample design is utilized to estimate watershed evapotranspiration water losses. Basically, there are three increasingly resolved levels of information, each of which is sampled. The first level is composed of satellite and topographic data. Vegetation, terrain and meteorological types of information are defined for a convenient base resolution element, in this case a small group of Landsat pixels. The appropriate evapotranspiration equations, defined as Level I models, are able to perform adequately on this "least resolved" information available from the first data level.

After an estimate of evapotranspiration has been made for each basin resolution element, the resolution elements (here 4 x 4 or 5 x 5 blocks of pixels) are grouped into primary sampling units (PSU's). Based upon the variability among PSU's a sample of these units will be selected within each stratum for further sampling. Within each PSU selected, a series of secondary sampling units (SSU's) will be defined and photographed at large scale with light aircraft. The photographic SSU data along with nearby snow course and ground station calibrated meteorological satellite data will provide the second level of information resolution. Thus Level II evapotranspiration models employing more data types and more refined data will be used to generate evapotranspiration estimates for each SSU. A sample of two of the SSU's per PSU selected will then be randomly chosen for further analysis on the ground. For each of these SSU's selected, detailed ground measurements will be made of vegetation canopy geometry, color, etc. as well as of soil and litter-organic debris conditions. The detailed data from this third level of information will then drive Level III evapotranspiration prediction models. Since estimates of evapotranspiration will be for the entire ground area of the SSU photo plot, this third stage unit (TSU) will actually comprise a double sample of the SSU's.

The full watershed estimate of evapotranspiration can then be developed by first using the ground based evapotranspiration estimate to calibrate the SSU estimate derived from photo data. The calibrated SSU estimates can then be expanded to the PSU stage by utilizing the SSU selection weights developed earlier. Finally, PSU evapotranspiration estimates can be expanded, each over the appropriate stratum, and then to the entire watershed by applying the PSU selection weights (proportion of evapotranspiration in the given PSU relative to all other PSU in the watershed) originally calculated. In this way, a cost-effective combination of an increasingly smaller sample of more precise and more expensive information levels can be utilized to give basin-wide watershed estimates.

The multistage equation that will be used to combine data from levels I, II, and III in order to generate an estimate of watershed-wide evapotranspiration is:

$$ET = \frac{1}{n} \sum_{i=1}^n \frac{1}{P_i} \left[\frac{1}{n_i} \sum_{j \in (D)} \frac{A_i}{a} \times \frac{Y_{1j}}{P_{1j}} \right], \text{ in which}$$

$$P_i = \frac{ET_i}{\sum_{i=1}^n ET_i} \quad \text{and} \quad P_{1j} = \frac{ET_{1j}}{\sum_{j \in (D)} ET_{1j}}, \text{ where}$$

- n = number of PSU's sampled (5).
- P_i = probability of selection of the i th PSU
- n_i = number of SSU's selected within i th PSU (2)
- $j \in (D)$ = the set of SSU's selected in each sampled PSU
- A_i = area of the section within which SSU is located
- a = area of SSU

- Y_{ij} = ground ET estimation for the jth SSU of the ith PSU
 P_{ij} = probability of selection of jth SSU for ground measurement within ith PSU
 ET = average evapotranspiration estimate for the entire watershed

This sampling technique allows the estimates of ET based on each level of modeling and if a user does not require high accuracy of ET estimates he/she can use the Level I models results independently or calibrated with Level II models results without having to use Level III models at all. Sampling theory allows a variance for each estimate. Therefore a confidence interval with specified probability may be associated with the estimates.

The required input data for this evapotranspiration estimation system is composed of physiographic data of the watershed and climatic data. Physiographic data include latitude, longitude, elevation, slope, aspect, and vegetation/terrain data. Climatic data include temperature, humidity, precipitation, wind movement, cloud cover, solar radiation, and some standard meteorological constants.

Recommended Level I ET Models:

Empirical and semiempirical formulas are applied in this level. The input for these models is provided primarily from Landsat, Environmental (meteorological) satellites, ground meteorological stations, and digital topographic data. The variables to be derived from these data for the above models are surface temperature, net solar radiation, relative humidity, precipitation, and cloud cover. The watershed values of net solar radiation are calculated based on a model developed by the author (Khorram, 1976). The models based on the following equations are being considered for this level: Jensen and Haise Equation (1963), Hargreaves Equation (1956), and Blaney-Criddle Equation (1950). Based on climatic conditions and models performances one of these equations is selected to represent the Level I models (Khorram, 1974 a, b).

Recommended Level II ET Models:

The basis for the evapotranspiration models to be applied to the second level of information resolution is that of energy conservation. For this level, the energy-balance method will be combined with other methods for consideration of vegetation canopy effects. The objective of the model applied at Level II will be to capitalize on vegetation canopy, geometry-composition, and other surface data available from aerial photography to provide improved evapotranspiration estimates for the appropriate photo SSU's (Khorram, 1975). The following models are being examined for application: Priestly and Taylor Model (1972), McNaughton and Black Model (1970), Modified Slatyer and McIlroy Model (1961), and Linacre Model (1967). Based on climatic conditions and models performances one or two of these equations are selected to represent the models in this level (Khorram, 1976).

Recommended Level III ET Models

The third information resolution level in this remote sensing-aided evapotranspiration estimation system will allow application of the practical as well as the most sophisticated models. The approach will be to select and develop those evapotranspiration estimation equations which are most rational and physical in terms of the actual processes involved. A combination of empirical, energy balance, and aerodynamic methods will be examined for this level. This model is to be developed in the future.

RESULTS

The results of snow areal extent, snow water content, and evapotranspiration are discussed respectively.

The estimates of the areal extent of snow and their confidence intervals for April 4th, May 10th, and May 28th are shown in Table II. The appropriate statistical parameters such as standard deviations, and population ratio estimator values are also presented in Table II. Additional Chi-square tests indicated that on all the dates the experimental set-up was adequate at 2.5 percent significance level.

The simulated infrared Landsat gridded imagery for the Feather River Watershed for April 4th, as an example, is shown in Figure 2. The summer (August 31) Landsat imagery is shown in Figure 3. The larger scale copies of these imagery (Figures 1 and 2) along with the gridded imagery for May 10th and May 28th were used in snow areal extent and consequently snow water content inventories.

The results of Landsat-aided snow water content estimates, based on Spanish Creek Watershed data, is shown in Table III. This data is used to represent Feather River Basin values due to the similarity in snow water content class distribution between the two basins for the snow season dates investigated. The correlation coefficients between the average ground-based and Landsat-based values of snow water content indices are 0.65 and 0.77 for three dates and two dates of analysis respectively. Since more than two dates will be available in most operational snow water content estimation situations, a conservative value of 0.80 was selected as the correlation coefficient to be used in the sample size analysis.

A side-by-side comparison of an operational and this Landsat-aided snow water content, estimation systems was facilitated by a blending of statistical and economic theory. This comparison, using 1974 data, was based on analysis of over 2200 image sample units at 15¢ each and 26 ground sample units at \$150 each. The analysis indicated a decided advantage for the Landsat-aided method (Sharp and Thomas, 1975).

Level I evapotranspiration models have been applied to Spanish Creek Watershed (SCW) for August 1972. The results are different in terms of accuracy depending on the model used. The model based on Jensen and Haise equation has yielded satisfactory results. The available ground meteorological stations within the Spanish Creek Watershed is shown in Table IV. All the input parameters for ET models are based on these ground meteorological stations. Currently, we are developing methodologies to obtain the main input parameters (i.e., temperature, cloud cover, etc.) from Landsat and NOAA satellites.

The areal distribution of the mean monthly temperature in °F and relative humidity in percent over the Spanish Creek Watershed were used as inputs to ET models. Watershed-wide distribution of average monthly consumptive use (potential ET) estimates based on Blaney-Criddle equation is shown in Figure 4. This method has been developed primarily for agricultural crops and the results appear to be higher than expected. Based on the Hargreaves equation, the average free water surface evaporation map of August 1972 was calculated and the results seem to be higher than the expected values. Daily potential evapotranspiration estimates of August 14, 1972, based on the Jensen and Haise model, is shown in Figure 5. The results of the Jensen and Haise model seems to be closer to the values initially expected than the Blaney-Criddle and Hargreaves methods. Based on the performance of the Level I evapotranspiration models it can be concluded that the Hargreaves model may not be directly applicable to the forested watersheds without major modifications.

The results of ET level I models utilizing solar radiation and temperature data on the main variables (i.e., the models of Jensen and Haise) are more applicable to the watershed diversified evaporative surfaces present in the Spanish Creek Watershed. Nevertheless, slight modifications based on the ground measurements of evapotranspiration values may be required depending on the accuracy desired.

CONCLUSIONS

Based on the evaluation of the procedures developed in this investigation and analysis of results it can be concluded that:

The methods developed in this investigation are different from the traditional methods reported in the literature.

The double sampling method which in effect "calibrates" the Landsat imagery provides a good way of analyzing the data. The general approach multistage sampling has been used successfully in several other remote sensing research experiments involving manual and computer-aided analysis by many investigators at the University of California. The design of this project facilitates the performance of valid statistical analysis. This is an important factor so that future results from different approaches can be analyzed with respect to prior research. Cor-

confidence intervals were applied to all the data processing thus providing accuracy of results figures.

Remote sensing data can be integrated with conventional data for more accurate and location-specific analysis of major inputs in water yield forecast models. Advantages of the remote sensing-aided systems are also apparent on the capability and/or cost effectiveness side.

The preliminary analysis of the results on evapotranspiration models indicated that models using solar radiation and temperature as the main input variables are more applicable to the watershed environmental conditions than those using temperature and humidity.

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Landsat Snow Water Content Stratum	1	2	3	4	5	6
Index Range (mm)	<0.10	614	<1.00	<3.00	5.00	283
No. of Landsat ISU's Examined in Watershed	503	614	205	393	220	283
No. of ISU's Visited on Ground	0	3	1	7	4	11

Table I. Required Image and Ground Sample Units for all the Snow Water Content Strata.

	April 4, 1973	May 10, 1973	May 28, 1973
Landsat-1 estimate of the areal extent of snow	511,378	205,768	60,516
Estimate of the true areal extent of snow	501,355	195,644	57,847
Standard deviation of the areal extent of snow estimate	12,776	14,526	17,126
Population ratio estimator	.9804	.9509	.9559
Total number of hectares inventories	879,642	813,014	798,340
Total number of image sample units inventories	2,218	2,050	2,013
Total number of image sample units sampled	80	52	49
Confidence intervals (95%)	$485,940 \leq Y_R \leq 536,816$	$176,601 \leq Y_R \leq 234,935$	$26,075 \leq Y_R \leq 94,958$

Table II. SUMMARY OF RESULTS AREAL EXTENT OF SNOW ESIMATION (IN HECTARES) ALONG WITH THE CONFIDENCE INTERVALS.

Stratum Index (h)	Landsat-1 Snow Water Content Estimate Range	Ave. Snow Water Content Index Per Image Sample Unit $X_h = \frac{\sum_{i=1}^{n_h} x_{hi}}{n_h}$	Standard Deviation for X_{hi}	Coef- ficient of Varia- tion	Total Snow Water Content Index $X_h = \sum_{i=1}^{n_h} X_{hi}$	Stratum Weight Based on Snow Water Content $W_h = \frac{X_h}{\sum_{h=1}^6 X_h}$	Number of Image Sample Units for the Spanish Creek Watershed	Number of Image Sam- ple Units For the Feather River Watershed
1	0.00- 0.10	0.0000	0.0000	0.00	0.00	0.0000	32	503
2	0.10- 0.35	0.1833	0.1194	65.14	7.15	0.0304	39	614
3	0.35- 1.00	0.7808	0.1883	24.12	10.15	0.0432	13	205
4	1.00- 3.00	2.0480	0.4404	21.50	51.20	0.2178	25	393
5	3.00- 5.00	3.9557	0.4525	11.44	55.38	0.2356	14	220
6	5.00	6.1750	0.9672	15.66	111.15	0.4729	18	283
							N _h =141	N=2,218

Table III. LANDSAT-BASED SNOW WATER CONTENT STATISTICS BASED ON SPANISH CREEK WATERSHED DATA FOR APRIL 4, MAY 10, AND MAY 28, 1973.

C-10

Station	lat	lat	UTM($\times 10^3$) X	Y	Dates of data
Quincy	120°57'	39°55'	675.63	4422.57	72*, 75 [†] & 75 [‡]
Greenville	120°56'	40°08'	675.19	4445.11	72* & 75 [†]
Boulder Creek	120°37'	40°12'	703.25	4442.34	72* & 75 [†]
Mohawk	120°38'	39°47'	702.62	4406.53	72* & 75 [†]
Camel Peak	121°06'	39°43'	662.84	4398.22	72* & 75 [†]
Smith Peak	120°32'	39°52'	711.32	4415.75	72* & 75 [†]

* = Wet bulb temperature, dry bulb temperature, daily temperature relative humidity, precipitation, and wind speed and direction.

† = Daily average temperature, relative humidity, precipitation, and wind speed and direction.

‡ = Wet bulb temperature, dry bulb temperature, daily average temperature, evaporation, precipitation, cloud cover, and day length.

Table IV. AVAILABLE DATA FROM GROUND METEOROLOGICAL STATIONS IN THE SPANISH CREEK WATERSHED REGION

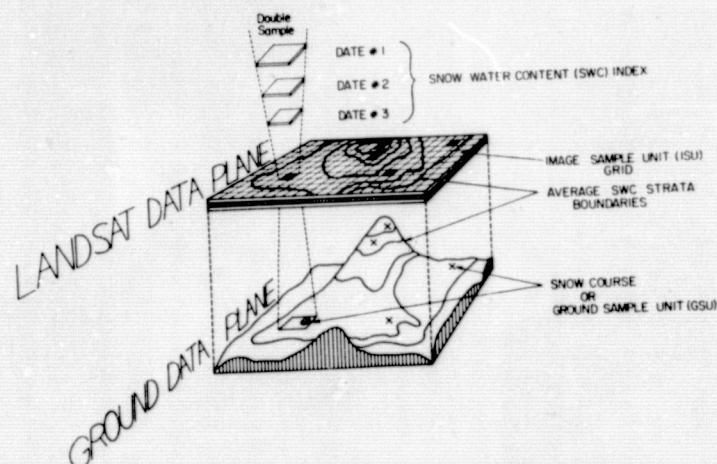


FIGURE 1. Stratified multirate Landsat data plane calibrated by snow course measurements for watershed snow water content estimation.

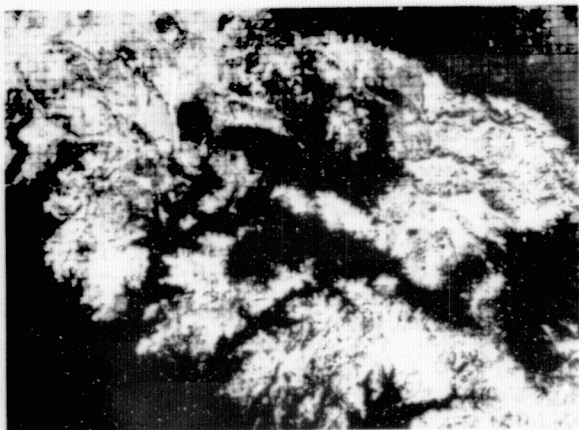


FIGURE 2. Landsat-1 simulated color infrared imagery for April 4, 1973 over Feather River Watershed. Each image sample unit (grid box) equals 400 hectares.

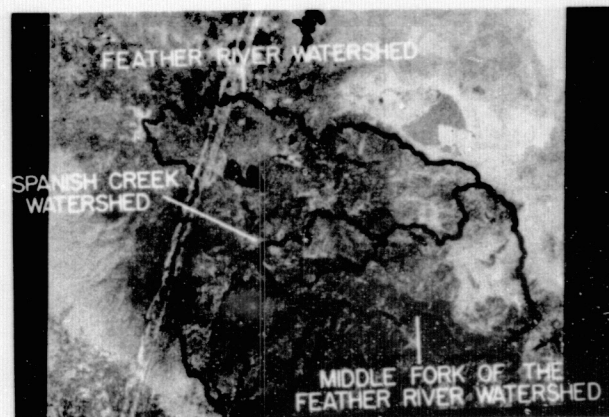
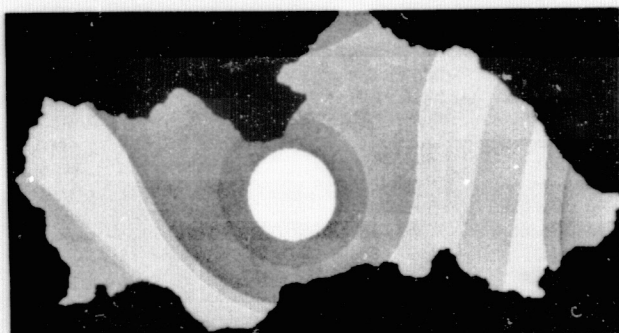
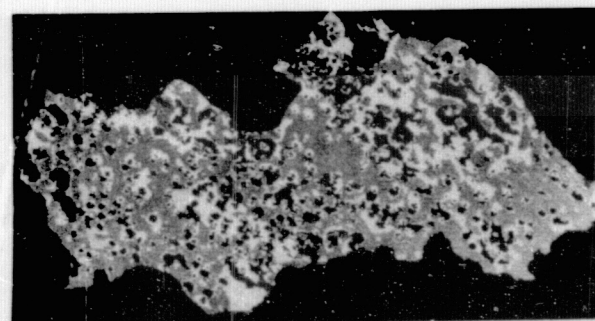


FIGURE 3. Landsat-1 simulated color infrared imagery for August 31, 1972 over the Feather River Watershed.



LET 1 MODEL, BC, SCW, AUG. 72

FIGURE 4. Areal distribution of average monthly evaporation in inches of water for August 1972, Spanish Creek Watershed, based on Blanney-Criddle Equation. Light purple = 16.13, Dark purple = 16.30, Darker purple = 16.47, Orange = 16.50, Yellow = 16.65, Gray = 16.87, Green = 17.00, Blue Green = 17.45, Dark Blue = 17.67, Saturated blue = 17.85, White = 18.00



LET MODEL 3, SCW, AUG. 14, 1972, SK

25

FIGURE 5. Areal distribution of daily potential evapotranspiration estimates in inches for August 14, 1972, over the Spanish Creek Watershed, based on the Jensen and Haise equation. Red = 0.1-0.23, Orange = 0.23, Yellow = 0.29, Brown = 0.30, Green = 0.31, Green blue = 0.31, Blue Green = 0.32, Blue = 0.33 - 0.38

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APPLICATION OF AERIAL PHOTOGRAPHY TO
WATER-RELATED PROGRAMS IN MICHIGAN*

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ABSTRACT

The paper describes the use of aerial photography and information system technology in the provision of information required for the effective operation of three water-related programs in Michigan. Potential mosquito breeding sites were identified from specially acquired low altitude 70 mm color photography for the City of Lansing Vector Control Area. The inventory identified 35% more surface water areas that were indicated on existing field maps and treatment of these areas will lead to a more effective mosquito eradication program. A comprehensive inventory of surface water sources and potential access sites was prepared to assist fire departments in Antrim County with fire truck water-recharge operations. Remotely-sensed land cover/use data for Windsor Township, Eaton County were integrated with other resource data into a computer-based information system for regional water quality studies. Eleven thematic maps specifically focussed on landscape features affecting non-point water pollution and waste disposal were generated from analyses of a four-hectare grid-based data file containing land cover/use, soils, topographic and geologic (well-log) data.

INTRODUCTION

Michigan State University, with support from the Office of University Affairs of the National Aeronautics and Space Administration, has been actively involved in the development of operational uses of remote sensing for improving decisions and actions concerning land and water resource problems. Three recent applications to water-related programs in Michigan are presented and they demonstrate the diversity of concerns that require an adequate inventory for satisfying planning interventions and on-land actions.

INVENTORY OF POTENTIAL MOSQUITO BREEDING SITES

Mosquitoes have always been a nuisance during the late spring and summer in Michigan. The outbreak of St. Louis Encephalitis in 1975 transformed this nuisance into a potentially major health hazard as this strain of encephalitis virus, transmitted by mosquitoes, is potentially fatal. It is thus a target of public health prevention and control measures.

The Vector Control Section of the City of Lansing, established in 1959 by the Center for Disease Control, U.S. Department of Health, deploys several field teams each year to treat standing water and wetland areas with appropriate compounds for mosquito larvae extermination. Effective eradication is crucially dependent upon the identification and treatment of all potential breeding sites. The teams have been using a series of field maps showing treatment sites which

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were prepared in 1960. A sample aerial survey, conducted in the spring of 1975, revealed that these field maps indicated only 50 percent of the number of potential breeding sites in a 16 square kilometer test area. Non-treatment of this number of potential sites seriously jeopardizes the overall eradication effort.

A comprehensive inventory of standing water (as small as puddle size) and wetlands in the Lansing/East Lansing area (233 square kilometers) was therefore undertaken by the Remote Sensing Project in 1976. Using a motorized Hasselblad camera, 70 mm color transparencies were acquired for the area at a scale of 1:18,000. Coverage was obtained from a small plane during the spring when water levels were at their highest. The photography was systematically interpreted using a zoom stereoscope (24X magnification). Identified potential breeding sites were delineated on clear acetate overlays and then transferred to a specially prepared mylar base map of each township section (Figure 1). A total of 90 maps were prepared at a scale of 1:6,700 and sequenced to facilitate easy field use. Paper copies of the original maps were produced to an 8½x11" format and these copies, protected in acetate jackets, were included in a three ring binder to be used as the primary reference document for the field treatment crews. A map showing the standing water/wetland distribution for the entire Lansing/East Lansing area was also prepared (Figure 2).

At the beginning of eradication activities in 1977, specific treatment information pertaining to individual sites will be indicated on the field maps including sequence of treatment within township sections, permanency of water, access points, obstacles to treatment and type of treatment (adulticide, larvicide, fish stocking). These maps will then be used in the systematic treatment of mosquito breeding sites throughout the year.

The standing water/wetland inventory identified 2,078 potential treatment sites consisting of 476 waterbodies, 1,222 wetlands and 380 drains or river segments. Ground verification of this data in a particularly wet test area (29 square kilometers) revealed that the field teams were treating only 19 percent of the existing sites: 40 as compared with 211. Overall the photo-derived inventory identified approximately 35% more water areas than were indicated on the existing field maps used by the treatment teams.

Traditionally, mosquito control districts collect data on potential breeding sites through tedious ground surveys. These data are often fragmentary, since ground surveillance locates only the most obvious sites. After years of data acquisition and much expense in time and man power, the control district usually has an indication of where mosquito control should be implemented. Through photo-interpretation of aerial photography, potential breeding sites can be identified in a more timely, cost-effective manner. The Lansing standing water/wetlands inventory was completed within three months at an estimated cost of \$3,835 which included acquisition of aerial photography.

IDENTIFICATION OF SURFACE WATER ACCESSIBLE TO FIRE TRUCKS

A major problem in Antrim County is locating accessible water sources for use by fire fighting units. All units reporting to a fire outside of village or city limits have an on-board water supply. When this supply is expended, the unit has to recharge its tanks. The trip to recharge should be as brief as possible and information regarding the nearest accessible water source is crucial.

MSU personnel identified and delineated all surface water areas in Antrim County of at least 0.2 hectares from 1:36,000 color-infrared photography acquired by the Michigan Department of State Highways and Transportation in 1973. The name, type (e.g. natural lake, intermittent stream), size and depth of each water area were recorded based on the classification system given in Table I.

Potential access sites for recharging fire truck water supplies were then identified from the photography. For each identified access site, a determina-

tion was made from the photography as to the type of access route, the intervening land cover or land use and possible limitations to recharging such as water depth, the presence of aquatic vegetation or slope restrictions. The ownership of the access sites, as given in the county plat book, was also identified. The accessibility classification system employed is also cited in Table I.

The locations of water sources and identified access points were transferred to a series of mylar township base maps at a scale of 1:36,000 (Figure 3). A unique identifier code was assigned to each water source and access point and these codes, along with the corresponding information on water characteristics and accessibility parameters, were recorded on a computer file. This file allows the output of information in various formats and facilitates modifications based on feedback from the fire fighting units. The township map file and computer listing are being used during fire fighting situations to locate the closest suitable water source and access point from the site of a fire. It is expected that this information will increase fire fighting efficiency and, in as many cases as possible, lessen fire damage and reduce consequent property losses.

RESOURCE INVENTORY FOR REGIONAL WATER QUALITY AND LAND USE PLANNING

Traditionally, there has been a need for systems which will allow agencies to integrate remotely-sensed land cover/use information with other natural resource information in order to generate the analyses necessary for effective decision making. Water quality programs require such integration of data from a wide variety of sources.

For small area watersheds, adequate planning can be accomplished by manual analysis on individual maps of basic resource data: soils, land cover/use, topographic, etc. This approach, however, enjoys no economies of scale, and the extension of water management priorities to large-area watersheds places the resource planner in a position of seeking new tools to accomplish the desired goals. As the study area increases, manual analysis becomes less attractive as a viable alternative for investigating watershed management strategies and computer-assisted analytical approaches become more practical and cost-effective. This is particularly the case when a data base can be assembled that serves a multiplicity of uses for local resource decision-making. The MSU Remote Sensing Project has been developing various computer-assisted techniques that are designed to service a broad spectrum of resource management problems.

A demonstration of this approach to resource analysis was conducted in Windsor Township, Eaton County, Michigan, in cooperation with the Tri-County Regional Planning Commission. The demonstration was funded through a regional water quality grant, therefore the types of data gathered, and the subsequent analyses were specifically focused upon various aspects of non-point water pollution and suitabilities for selective land uses.

The Commission contracted with MSU for the provision of land cover/use data for the region and its integration with other information for a selected township. A 21-category land cover/use map was prepared for Clinton, Eaton and Ingham counties from NASA color-infrared photography at scales of 1:60,000 or 1:120,000.

A resource management portfolio was then developed for Windsor Township, Eaton County, using the Resource Analysis Program (RAP) developed at Michigan State University. RAP is an interactive, user-oriented computer software system that utilizes grid geocoded resource data in a variety of analytical and mapping functions (Table II). Combining and sequencing these various functions of the program allows users to construct a wide variety of thematic maps.

In Windsor Township, remotely-sensed land cover/use, existing soils, topographic, and subsurface data were coded for each cell of a four-hectare grid ma-

trix. The data were comparatively analyzed by employing various algorithms of RAP, such as standard overlay technique and site index scaling to produce eleven thematic maps related to water quality management.

By selectively analyzing individual data within the information system, such as soil type, and by multi-factor analytical methods, maps were constructed of potential nutrient and sediment loading areas, ground-water recharge areas, and limitations for different types of waste disposal practices (Figure 4). The maps are at a scale of 1:24,000 and were drawn on a mylar base by a computer-driven plotter. This type of mapping option permits the user to overlay the thematic maps on a 7.5 minute topographic quadrangle or other available base maps. Furthermore, inexpensive map copies can be made using a diazo blueprint machine. If user requirements so warrant, the individual map categories can be produced on separate mylar sheets for recompilations as a final color product. RAP is supported by several internal libraries on soil properties and crop yields. Over twenty soil engineering or related site development properties can be retrieved by the program, or the yield for the major crops of the state can be determined for soil-slope combinations. These soil properties can be displayed individually, such as soil phosphorus levels or combined with other data in multi-factor analyses.

The RAP system as used in the Windsor Township study was oriented toward water quality management, although the program and the data base have wide applicability to other local programs, including highway and drain construction, land use planning and zoning, land assessment, and forest management. The unique analytical and graphic capabilities of the Resource Analysis Program provide a powerful tool for many regional planning and resource management programs.

SUMMARY

In two of the applications described, an inventory of surface water information was acquired through interpretation of aerial photography. Mapping the location of surface water areas that potentially foster mosquito populations provided the information necessary to improve the eradication program in the Lansing Vector Control Area. A similar inventory in Antrim County was combined with water access information and formatted in a rudimentary computer information system so that water could be effectively used as a resource in fire fighting operations. The third application did not require specific information on surface water characteristics. Land cover/use information derived from aerial photography was, however, an important data element in a grid-based computer information system developed for water quality planning in Windsor Township, Eaton County. Eleven thematic maps were produced which allowed evaluation of potential non-point nutrient loading areas and physical limitations or suitability or selected land uses.

Table I. Antrim County Waterbody Inventory: Classification Scheme

Name: The name of the waterbody as given on U.S.G.S. topographic maps or other sources.

Type: All water areas have been classified from the photography as to their origin. Classes of surface water recognized were:

- | | |
|-----------------------------|--------------------------|
| 1. Natural lake or pond | 11. Fish hatchery |
| 2. Natural lake with dam | 12. Flooded borrow pit |
| 3. Artificial lake | 13. Recharge basin |
| 4. Artificial pond | 14. Settling pond |
| 5. Hydro-electric reservoir | 15. Beaver pond |
| 6. Municipal water supply | 16. Waste treatment pond |
| 7. Wildlife flooding | 17. Fish breeding pond |
| 8. Mill Pond | 18. River or creek |
| 9. Gravel Pit or quarry | 19. Intermittent lake |
| 10. Marl lake, dredged | 20. Intermittent stream |

Size: The area of the lake or the width of the stream or river. The area or width of other waterbodies was estimated from the aerial photography.

Depth: Maximum depth as reported in the Michigan Lake Inventory Bulletin.

Access Type: Type of surface of access route.

- | | |
|-----------------|------------------|
| 1. Paved road | 7. Pipeline |
| 2. Boat landing | 8. Powerline |
| 3. Dirt road | 9. Driveway |
| 4. Open field | 10. Private yard |
| 5. Farm lane | 11. Bridge |
| 6. Fire lane | 12. No access |

Land Use: The land cover or land use of the access site.

- | | |
|-------------------------|--------------------------|
| 1. Residential | 7. Cropland |
| 2. Commercial | 8. Pasture |
| 3. Industrial | 9. Orchards |
| 4. Water transportation | 10. Farmsteads |
| 5. Road transportation | 11. Herbaceous rangeland |
| 6. Urban open and other | 12. Shrub |

Access Ownership: Private or public.

Possible Limitations: Possible limitations to recharging fire truck water supply.

1. Depth--shallow water source, may pose restrictions in dry periods
2. Vegetation--presence of aquatic vegetation may limit pump functioning near the shoreline
3. Wet--site surrounding access point may cause access problems in wet periods
4. Slope--the slope of the access site may cause access problems

Table II. Phases of RAP and Their Function

<u>Phase</u>	<u>Function</u>
1. AGVALUE	Determines State equalized assessment values for agricultural land
2. DELETE	Delete a factor from the Work File
3. END	Stops execution of RAP
4. EROSION	Calculate on-site erosion susceptibility according to the Universal Soil Loss Equation
5. GROUP	The factor values are grouped and each group is assigned an integer number (mapping directive), default or user specified
6. INVERT	Invert the numerical range of a factor
7. LIST	Lists the factor names currently on the Work File
8. MAPIT	Constructs symbol maps with a plotter
9. NORMALIZE	Normalize the numerical value of a factor between user specified or default range
10. OVERLAY	Generates comparative site indices by overlay process with weighting values
11. PRINTERMAP	Constructs symbol maps from a line printer
12. SCALE	Generates comparative site indices by a multi-dimensional scaling algorithm
13. SOILTABLE	Retrieves soil and/or slope related properties
14. SORT	Assigns a value (mapping directive) to pairwise combination of factors
15. STATISTICS	Generates frequency table for factor values
16. UPDATE	Updates the master file by adding or deleting factors
17. WORKFILE	Retrieves factors from master file and places them on the Work File

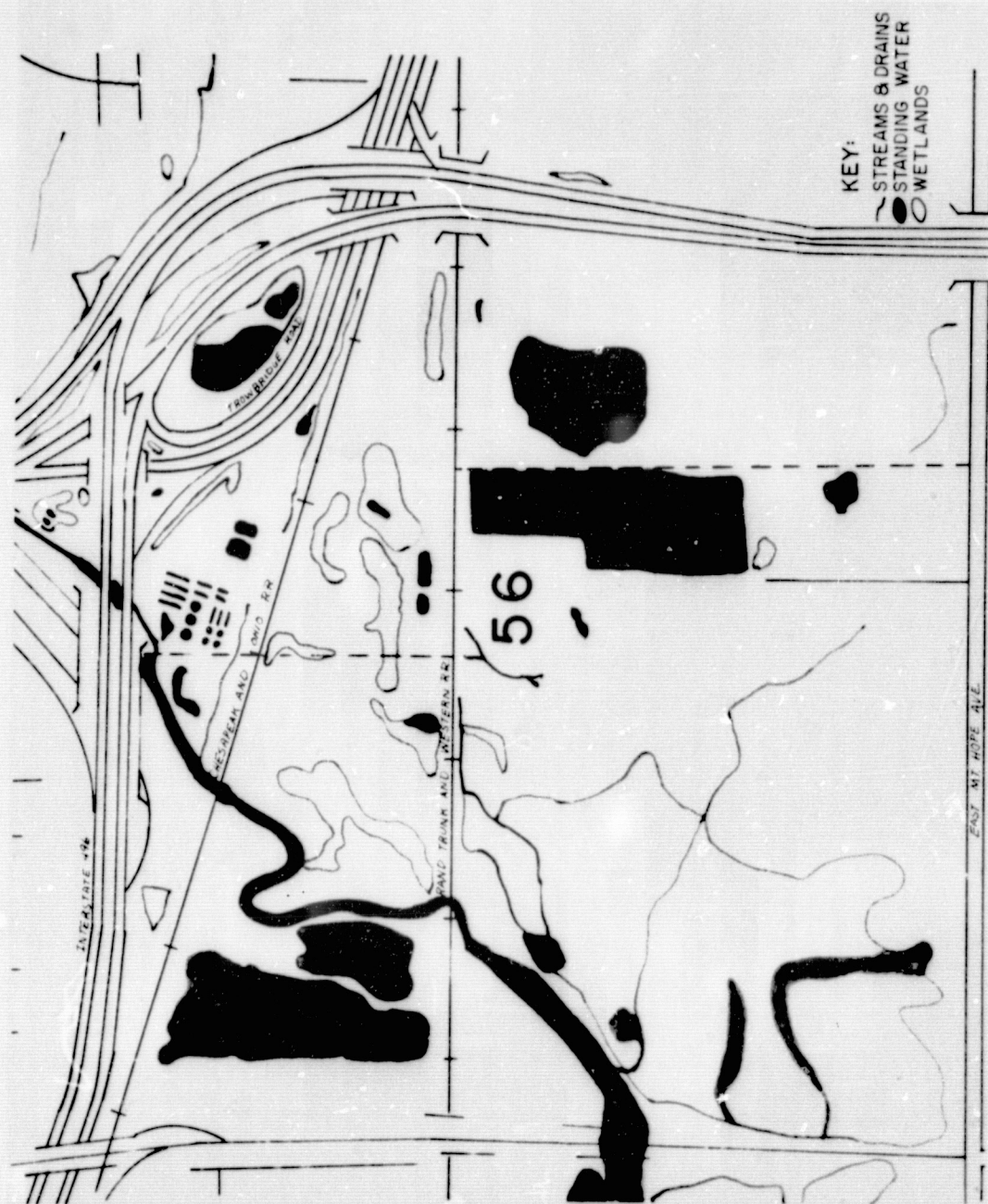


Figure 1. Potential Mosquito Breeding Sites in One Section of Lansing Township

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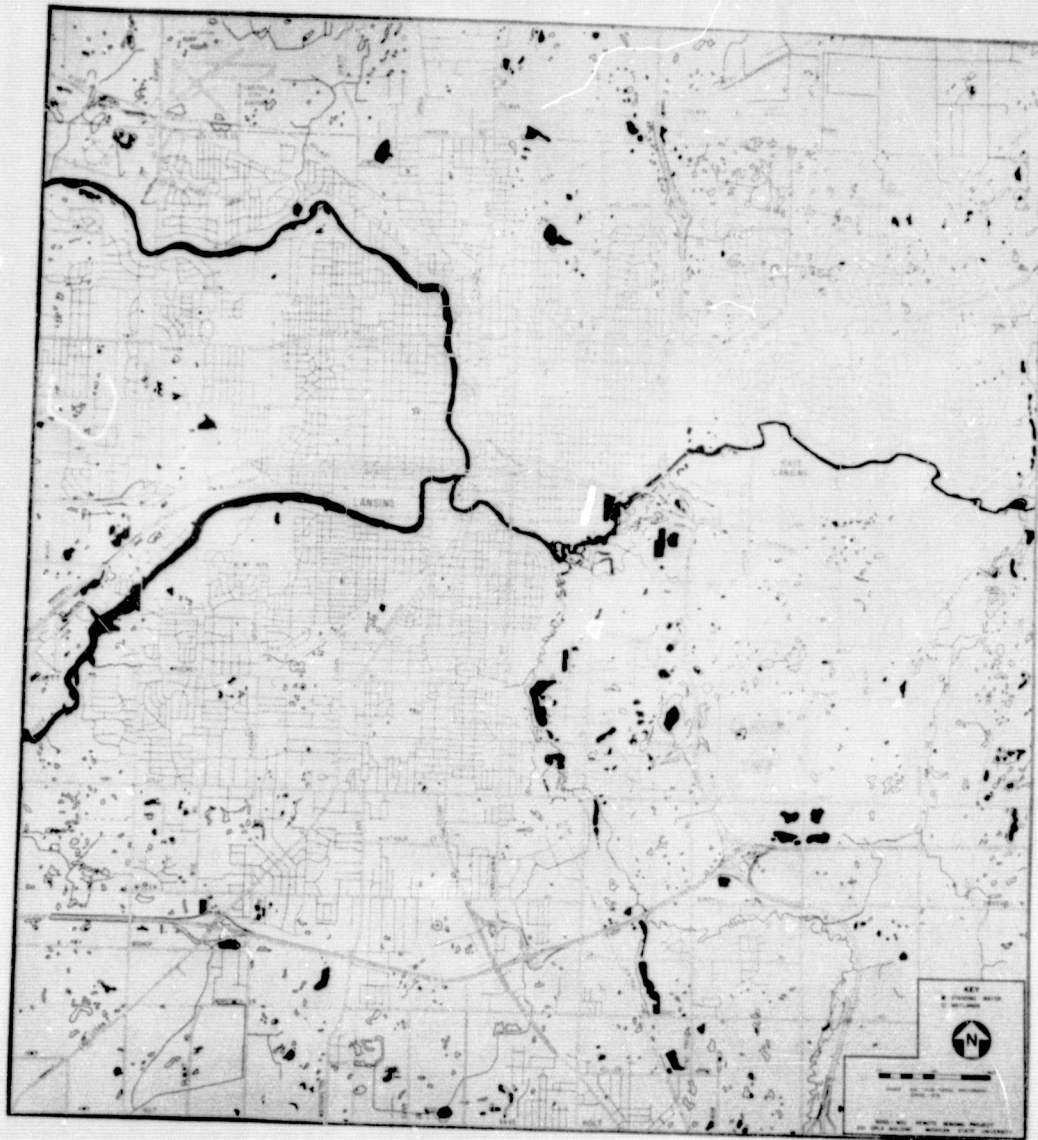


Figure 2. Standing Water/Wetlands Inventory:
Lansing, East Lansing Vector Control Area

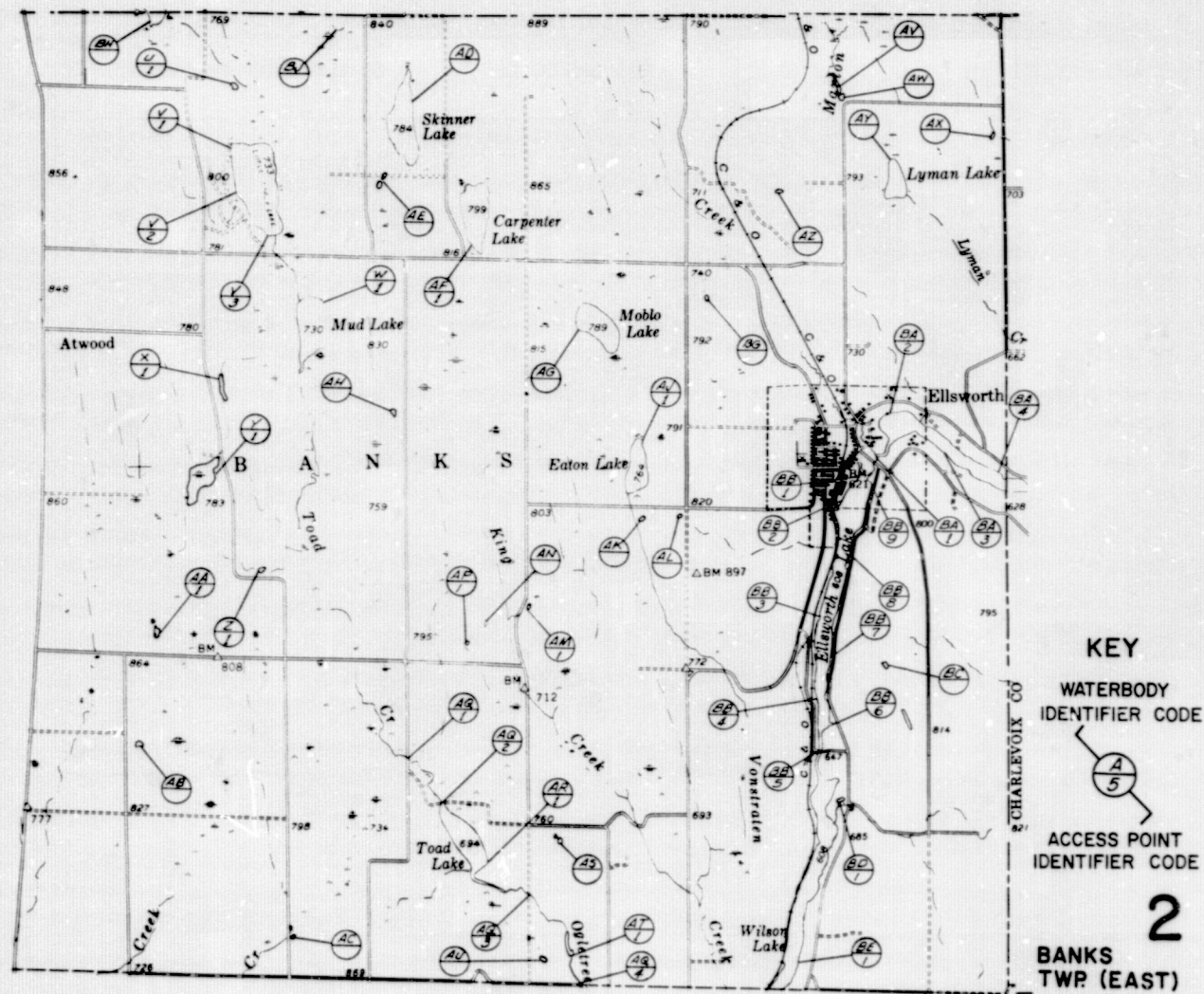


Figure 3. Waterbody/Access Point Map: Banks Twp. (East), Antrim Co.

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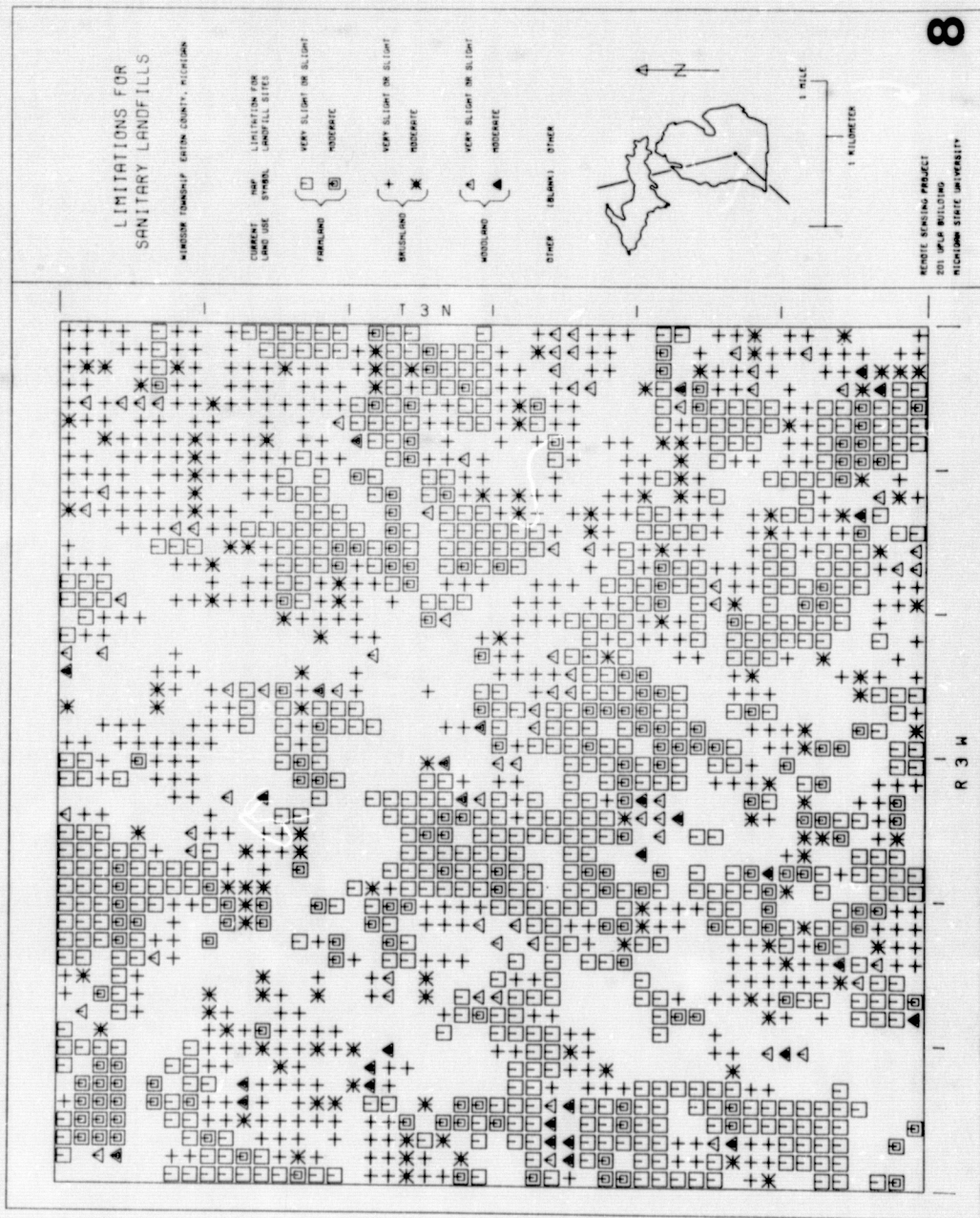


Figure 4. Example of a Resource Analysis Program Map

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